CORTICOSPINAL AND SPINAL RESPONSES AND ADAPTATIONS FROM SHORTENING AND LENGTHENING RESISTANCE TRAINING AND SUBSEQUENT DETRAINING

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Abstract

Maximising strength and neurological adaptations to resistance training has long been sought to improve athletic performance and enhance clinical rehabilitation functional outcomes. In recent years, transcranial magnetic stimulation (TMS) and peripheral nerve stimulation (PNS) have been applied to investigate changes in the central nervous system (CNS). Conventional resistance training programmes consist of shortening and lengthening muscle contractions and have been shown to have uniquely different motor control strategies; how this neurological control is modified during specific muscle contraction resistance training is unknown. Additionally, understanding the detraining process will assist in designing tapers for elite athletes and improve our knowledge of detraining and inactivity in other populations. The overall aim of the thesis was to determine the TMS and PNS responses to, and following, shortening and lengthening resistance exercise and subsequent detraining.

Initially, the day-to-day reliability of TMS and PNS responses during shortening and lengthening muscle contractions were determined. TMS and PNS showed good between day repeatability. However importantly, the work highlighted an increase in resting motor evoked potentials (MEP) from the initial exercise and therefore suggested a familiarisation session was warranted to improve the repeatability.

Secondly, there was an examination of the TMS and PNS responses in chronic resistance trained and untrained individuals during shortening and lengthening muscle contractions. Despite the greater maximal voluntary contractions shown in all muscle action types for the chronically trained volunteers, there were no differences in TMS and PNS responses between trained and untrained individuals during shortening and lengthening contractions. However, the data from the second part of the chapter showed a reduction in MEP variability at rest following a familiarisation session, suggesting greater plasticity of the CNS in resistance trained individuals.

The final experimental chapter investigated 1) the TMS and PNS responses following 4 weeks either shortening or lengthening resistance training and 2) the subsequent detraining effect. Even though the study showed task specific strength adaptations, this was not paralleled with increases in corticospinal excitability. Conversely, the V-wave showed evidence of contraction-specific changes in strength. Despite up to a 12% decrease in strength (shortening MVC from shortening resistance training group) following 2 weeks detraining, strength showed a non-significant decrease in all groups. Whilst there was evidence of a decrease in corticopsinal excitability in both groups, V-wave was maintained throughout the 2 weeks detraining. In conclusion, clinical and sports practitioners should overload lengthening contractions during resistance training to maximise strength and neurological adaptations.

‘If you can’t explain it simply, you don’t understand it well enough’

Albert Einstein

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List of Abbreviations

ADP	Adenosine Diphosphate
ATP	Adenosine Triphosphate
CI	Confidence Intervals
CMEP	Cervicomedullary Motor Evoked Potential
CNS	Central Nervous System
CON	Control
CV	Coefficient of Variation
EEG	Electroencephalography
EMG	Electromyography
GABA	Gamma-aminobutyric Acid
H-Reflex	Hoffman Reflex
ICC	Intraclass Correlation Coefficient
ISO	Isometric
LEN	Lengthening
M1	Primary Motor Cortex
MEP	Motor Evoked Potential
M_{max}	Maximal M-Wave
MRCP	Movement Related Cortical Potential
MRI	Magnetic Resonance Imaging
MVC	Maximal Voluntary Contraction
PET	Positron Emission Tomography
PNS	Peripheral Nerve Stimulation
1RM	One Repetition Maximum
RFD	Rate of Force Development
rMT	Resting Motor Threshold
RT	Resistance Trained
SD	Standard Deviation
SHO	Shortening
SP	Silent Period
TA	Tibialis anterior
TES	Transcranial Electrical Stimulation
TMS	Transcranial Magnetic Stimulation
UT	Untrained

Publications arising from the Thesis

Peer-reviewed Papers

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Tallent J, Goodall S, Hortobágyi T, St Clair Gibson A, French DN, Howatson G. Repeatability of corticospinal and spinal measures during lengthening and shortening contractions in the human tibialis anterior muscle. *PLoS One*. 2012. 7:e35930.

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Conference Presentations

Howatson G. **Tallent J**, Goodall S, St Clair Gibson A, Hortobágyi T. Corticospinal and Spinal Variability During Lengthening and Shortening Contractions Performed by Trained and Untrained Males. Poster session presented at: American College of Sports Medicine 59th Annual Meeting; 2013 May 28 – June 1; Indianapolis, IN, USA.

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Tallent J, Goodall S, Hortobágyi T, St Clair Gibson A, French DN, Howatson G. Recovery time of motor evoked potentials following lengthening and shortening contractions in the human tibialis anterior muscle. Poster session presented at: The British Association of Sport and Exercise Sciences Annual Conference; 2011 Sept 6 – 8; Essex, UK.

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Author's Declaration

I declare that the work contained in this thesis has not been submitted in the past, or is to be submitted at any other University for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

The word count of this thesis is 38,775 words.

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Chapter 1: Introduction

1.1 Introduction

Increases in muscular strength are essential in both athletic and clinical populations. In an athletic population, increases in strength have been associated with a reduction in injury risk (Stone, 1990) and increase in physical attributes such as speed (Delecluse, 1997). From a clinical perspective, increasing strength in the elderly reduces the risk of falls (LaStayo *et al.*, 2003; Liu-Ambrose *et al.*, 2004), whilst an improvement in physical competency has been seen in stroke patients (Flansbjer *et al.*, 2008). In the early stages of resistance training, neurological adaptations are the prominent mechanisms increasing the maximal force generating capacity of the muscle (Sale, 1988; Aagaard, 2003; Gabriel *et al.*, 2006; Folland and Williams, 2007). Additionally, an increased force generating capacity of muscle has been shown after a single resistance training session, which is accompanied by a rapid adaptation in the neurological system (Muellbacher *et al.*, 2001). However, the mechanisms responsible for strength changes in the first few weeks are largely unknown. Understanding the magnitude of strength gains and how the central nervous system (CNS) is modified from different resistance training protocols will assist practitioners in maximising the efficiency of a resistance training programme.

Lengthening muscle contractions are often considered anti-gravity, that exert breaking forces through locomotion and work in tangent with shortening contractions to produce human movement (Isner-Horobeti *et al.*, 2013). The majority of resistance training programmes consist of both lengthening and shortening muscle contractions. Lengthening muscle contractions have unique control strategies when compared to shortening contractions, which ensures their frequent use in patient populations. More specifically, an increased cortical output during lengthening contractions demonstrating the complexity of the movement (Fang *et al.*, 2001; Fang *et al.*, 2004), whilst at a spinal level, there is greater inhibition (Duclay *et al.*, 2011). How the neurological system is modulated to contribute up to 80% greater MVC found during lengthening when

compared to shortening muscle contractions is unclear (Rodgers and Berger, 1974). Furthermore, there is evidence to suggest there is a greater increase in strength and neurological adaptation from lengthening resistance training (Hortobagyi *et al.*, 1996).

Whilst thousands of studies have created a diverse knowledge of resistance training adaptations, significantly less is known regarding the period following the cessation of resistance training. Detraining has been described as a partial or complete loss of training induced adaptation (Mujika and Padilla, 2000). Understanding the detraining process is vital for sport practitioners and clinicians. From a sporting view, it will improve the tapering period of athletes, whilst from a clinical perspective, it generates a greater knowledge for periods of inactivity such as post-operative recovery, illness and reduced activity with ageing. Despite the increasing area of interest, little consistency exists among findings. Studies have shown maintenance of strength above baseline levels for several months (Harris *et al.*, 2007; Popadic Gacesa *et al.*, 2011; Correa *et al.*, 2013). However, following only 14 days of inactivity in resistance trained athletes, a reduction in strength has been shown (Hortobagyi *et al.*, 1993). From a dynamic resistance training programme, lengthening contractions have been shown to preserve strength to a greater extent when compared to shortening contractions (Andersen *et al.*, 2005), suggesting lengthening contractions are less susceptible to detraining. However, the effect of solely lengthening or shortening detraining has not been appropriately addressed. Furthermore, Andersen *et al*. (2005) showed a greater preservation of lengthening contraction electromyographic activity (EMG) compared to a shortening contraction EMG. Although surface EMG provides a global measure of neurological drive to the muscle, it fails to distinguish between the sites of adaptation, which can reside in cortical, spinal and muscle sites.

In recent years, transcranial magnetic stimulation (TMS) and peripheral nerve stimulation (PNS) have been used to investigate neurological adaptations to resistance training. Numerous examples exist where TMS has been used to assess changes in corticospinal excitability and inhibition (Carroll *et al.*, 2002; Jensen *et al.*, 2005; Griffin and Cafarelli, 2007; Lee *et al.*, 2009; Kidgell and Pearce, 2010; Kidgell *et al.*, 2010; Latella *et al.*, 2012), whilst PNS techniques have assessed changes in spinal excitability (Aagaard *et al.*, 2002; Scaglioni *et al.*, 2002; Lagerquist *et al.*, 2006; Del Balso and Cafarelli, 2007; Holtermann *et al.*, 2007; Fimland *et al.*, 2009a; Ekblom, 2010). Despite the plethora of research, the different resistance training protocols and methods for assessing corticospinal and spinal related variables have led to few definite conclusions being drawn from the literature. Ensuring the resistance training programme is progressive, and CNS adaptations are assessed during the same conditions/method as the training, may lead to more definite conclusions.

Unlike acute neurological adaptations to resistance training, TMS and PNS have only been used in a limited number of studies to investigate chronic exposure to resistance training. At a cortical level, only one study has investigated changes in corticospinal excitability between chronic resistance trained and untrained individuals (Fernandez del Olmo *et al.*, 2006), showing little difference. However, adaptations were assessed during isometric contractions rather than during dynamic contractions. More conclusive findings have been shown at a spinal level (Milner-Brown *et al.*, 1975; Upton and Radford, 1975), though only a few muscles have been examined. To date, no single study has investigated TMS and PNS responses in a single experimental setting to assess how chronically resistance-trained individual's CNS is modified to support the increased force generating capacity of the muscle. Furthermore, tension related measures appear to be down regulated only during lengthening contractions (Amiridis *et al.*, 1996). Therefore, it is logical to suggest any modification in the CNS will be more prominent during a dynamic muscle action.

TMS and PNS are known to be highly reliable techniques for assessing neurological modifications (Palmieri *et al.*, 2002; Kamen, 2004; Darling *et al.*, 2006). Research predominantly uses these techniques at rest or during isometric conditions; whilst these conditions may reduce the error of the test, everyday tasks use dynamic muscle contractions and thus the external validity is questionable. However, assessing TMS and PNS during dynamic contractions is problematic; a result of the muscle changing length, causes the skin to move along the muscle, thus determining the repeatability of TMS and PNS related measures are during dynamic contractions is critical.

Research investigating neurological adaptations to shortening and lengthening resistance training has predominantly used surface EMG as a global measure of neurological system adaptations. Examining acute and chronic TMS and PNS responses following shortening and lengthening resistance training may increase our understanding of where neural adaptations occur to increase the maximal force generating capacity of the muscle. Additionally, with little evidence investigating cortical and spinal responses following the cessation of resistance training, TMS and PNS responses may give a greater insight into the process of detraining. Accordingly, the overall aim of this thesis was to investigate the corticospinal and spinal responses following acute shortening and lengthening resistance training programmes and subsequent detraining. In a course of three experimental chapters, this thesis specifically examines:

1) The reliability of TMS and PNS measures during shortening and lengthening muscle contractions.
2) The TMS and PNS responses in chronically resistance trained and untrained individuals during shortening and lengthening muscle contractions.
3) The acute (4 weeks) TMS and PNS responses from shortening and lengthening resistance training and subsequent detraining.

Chapter 2: Literature Review

2.1 Introduction

The aim of this literature review is to provide a broad and detailed overview of the available information regarding the role of lengthening and shortening muscle action resistance training on neural adaptations. The review will initially examine the nature of voluntary muscle contractions. It will then focus on techniques to monitor for specific changes within the nervous system (with specific emphasis on the CNS) and at multiple levels, which will converge on neurological adaptations to acute and chronic resistance training at a cortical and spinal level. As lengthening muscle contractions possess unique characteristics, the review will discuss why these play a key role in resistance training and clinical rehabilitation programmes. Finally, periods of inactivity or the cessation of resistance training will be evaluated.

2.2 Voluntary Muscle Contraction

In the short-term, the brain's principal role in motor control is to execute the action through managing perceptual and sensory feedback, whilst in the long-term, it is to acquire/retain motor patterns (Rosenbaum, 2010). The spinal cord, the brain stem and the cerebral cortex are the main areas that contribute to voluntary motor control (Enoka, 2008). Figure 2.1 shows the major brain areas involved in voluntary muscle contraction and their interactions. More complex tasks are prepared and executed in the higher centres of the CNS (Rao *et al.*, 1993), whilst voluntary reflexes movements can occur independently of supraspinal input (Stein and Thompson, 2006). The primary motor cortex (M1) has the largest concentration of corticospinal neurons that project on to skeletal muscle (Porter, 1985; Scott, 2008). Monosynaptic connections consisting of the pathway from the primary motor cortex to the spinal cord are termed the corticospinal tract (Enoka, 2008). Even though it has been known for 150 years that the M1 is organised somatotopically (Fritsch and Hitzig, 1870), it is only 50 years since electrical stimulation was used to identify the specific area responsible for the activation

of individual muscles (Woolsey *et al.*, 1952). Although M1 is the main area of the brain that controls voluntary movement of muscle, there are numerous areas of the nervous system that contribute to ensure successful completion of a locomotion task.

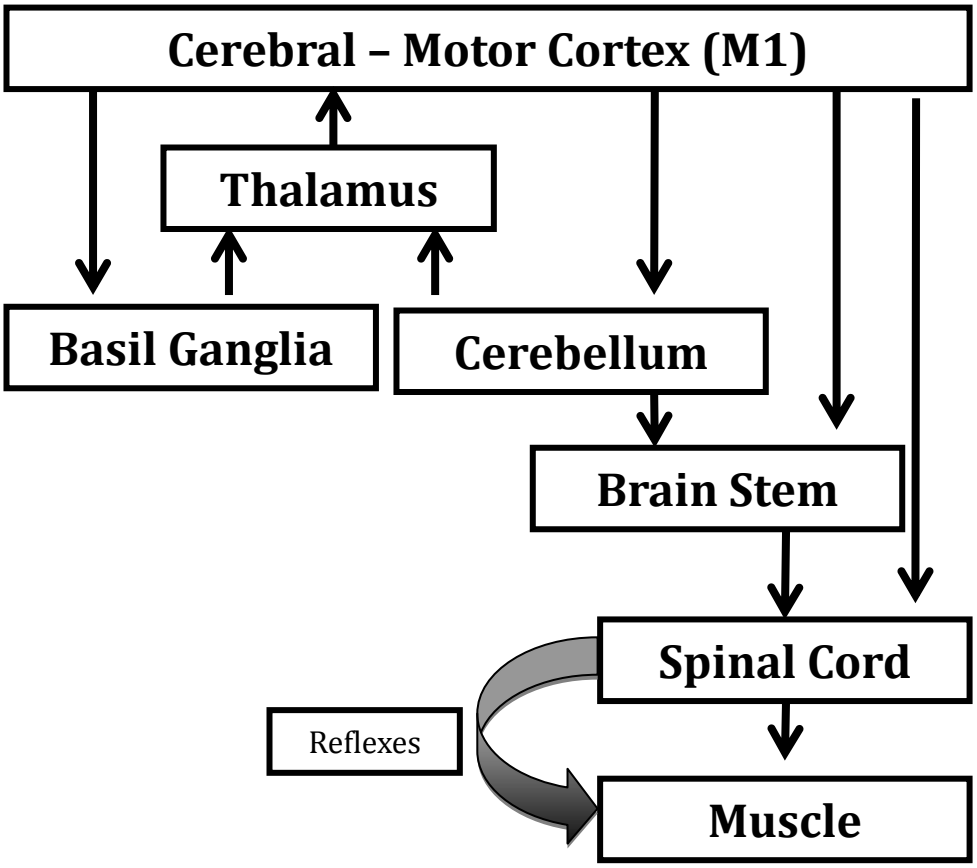

Figure 2.1 Schematic representation of the brain to muscle pathway and structures that are principally involved in human movement.

The pre-motor cortex and the supplementary motor area form part of M1 and play a secondary role in voluntary movement, where they are involved in planning and sequencing for successful completion of a task (Halsband *et al.*, 1993). The posterior partial cortex provides the premotor cortex and the supplementary motor area with sensory information to ensure the optimal motor programme is produced (Andersen *et al.*, 1997). Outside the motor cortex, the basal ganglia assists in organising more complex movements (Groenewegen, 2003), whilst the cerebellum inputs on the timing

of the tasks (Ivry *et al.*, 2002). The cerebellum and basal ganglia are sub-cortical areas that interact with the cerebral cortex through the neurons in the thalamus (Enoka, 2008). The brain stem is situated above the spinal cord and consists of three major components known as the mesencephalon, pons and medulla. Whilst one role of the brain stem is to connect the motor cortex to the spinal cord, it is also responsible for regulating the autonomous systems from sensory inputs (Lund, 1991; Enoka, 2008). Following initiation of the motor programme through an action potential or descending volley from M1 down through the brain stem to the spinal cord, the corticospinal fibres then activate neurons within the ventral horn of the spine and efferent neurons branch out towards the muscle. Figure 2.1 shows an outline of the brain to muscle structures that contribute to human movement. Briefly, once the action potential reaches the end of the motor neuron, the change in charge opens the calcium ion gated channel causing a calcium influx within the neuron. Consequently, the neurotransmitter acetylcholine is realised into the neuromuscular junction, which then binds to the ligand gated sodium channels. Subsequently, sodium is then released into the muscle, which generates an action potential that spreads across the T-tubles within the bundles of muscle fibres (McComas, 1996).

Post-synaptic, sodium is released by the sarcoplasmic reticulum. Myosin binding sites become available from the calcium ion binding to troponin, which causes the tropomoysin to expose the binding site. The active myosin site can then bind to actin to form a cross bridge, causing a muscle contraction. However, an adenosine triphosphate (ATP) must bind to the myosin head, which it is then hydrolysed to adenosine diphosphate (ADP) to activate the myosin head; only then can a cross bridge be formed. Once attached, inorganic phosphate is released which strengthens the actin myosin bond. Following this, ADP is released causing the myosin head to slide the myofilament towards the centre of the sarcomere (McComas, 1996). This

process is more commonly known as the sliding filament theory (Huxley and Hanson, 1954). Figure 2.2 shows the structure of the muscle.

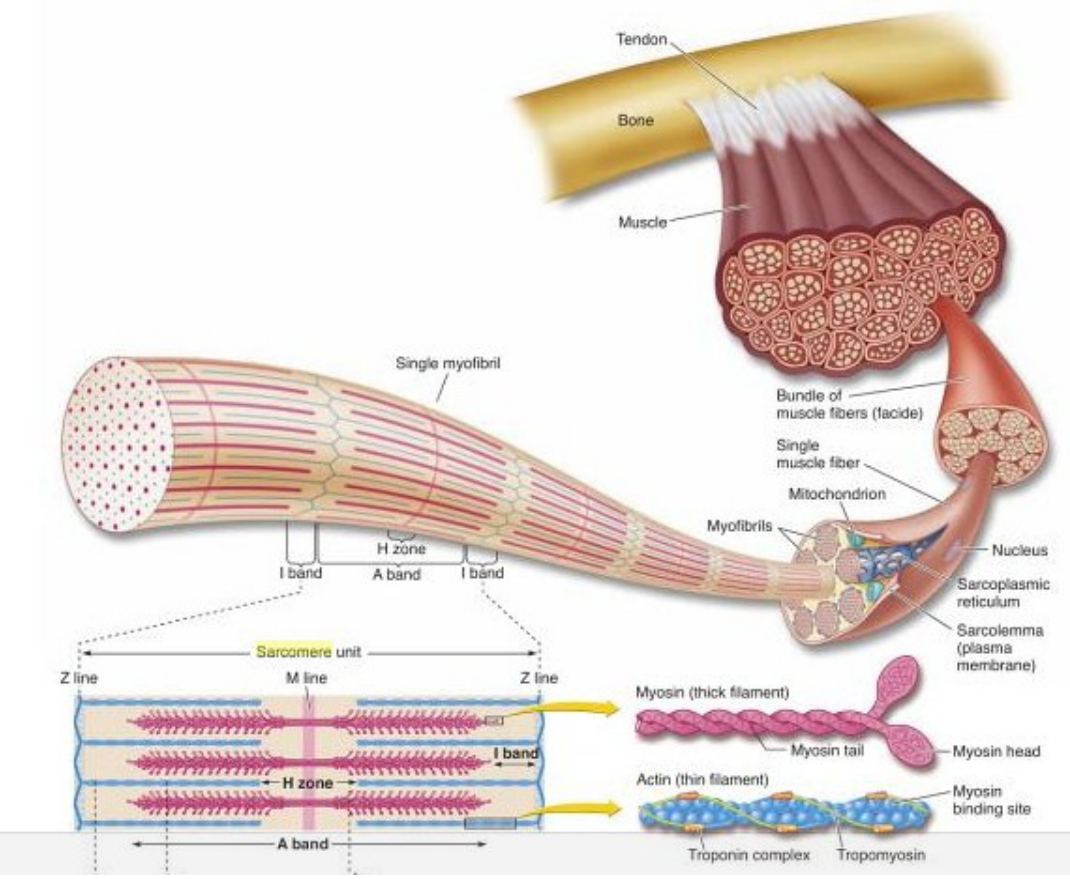

Figure 2.2 Illustration to show the structure of the muscle to a sarcomere unit composing of actin and myosin filaments (McArdle *et al.*, 2001).

2.3 Monitoring Neural Plasticity

Numerous techniques such as TMS (Kidgell and Pearce, 2011), transcranial electrical stimulation (TES) (Carroll *et al.*, 2002), electrical PNS (Aagaard *et al.*, 2002), magnetic resonance imaging (MRI) (White *et al.*, 2004) and positron emission tomography (PET) (Chollet *et al.*, 1991) are used to detect changes within the nervous system. Detecting these changes in the nervous system is critical for our neurophysiological understanding of neurological conditions and also to monitor the effectiveness of

exercise regimens and rehabilitation programmes; consequently this section will focus on TMS and PNS.

2.3.1 Transcranial Magnetic Stimulation (TMS)

Originally, Merton and Morton (1980) developed an electrical stimulator that was capable of producing an electrical shock over the primary motor cortex. This electrical stimulation produced a recordable electromyography (EMG) response at the target muscle called a motor-evoked-potential (MEP). However, due to the painful nature of electrical stimulation on the scalp, an alternative method for assessing corticospinal plasticity was needed. Barker *et al*. (1985) addressed this issue and developed a technique to activate the primary motor cortex with no pain. Transcranial magnetic stimulation (TMS) uses Faraday's principal, which states a rapidly changing magnetic field induces an electrical current (Faraday, 1839). In recent years this is applied via an intertwined copper coil attached to a magnetic stimulator. Such that, varying a magnetic field with time, in turn generates an electrical field. Magnetic fields pass with little resistance through the body and with a large enough field, an electrical current can be generated in neural tissue. Targeting cortical neurons by eliciting rapidly changing magnetic fields allows stimulation of specific muscles through the scalp (Hovey and Jalinous, 2006). Figure 2.3 shows a model of the motor homunculus. The figure demonstrates the various areas of M1 responsible for human movement and consequently the area to target through the coil. For a circular coil placed over the primary motor cortex, lines of flux are produced perpendicular to the plane of the coil (Hallett, 2000) (Figure 2.4). Current is induced in the opposite direction in the brain activating neurons that are within the field (Bolognini and Ro, 2010).

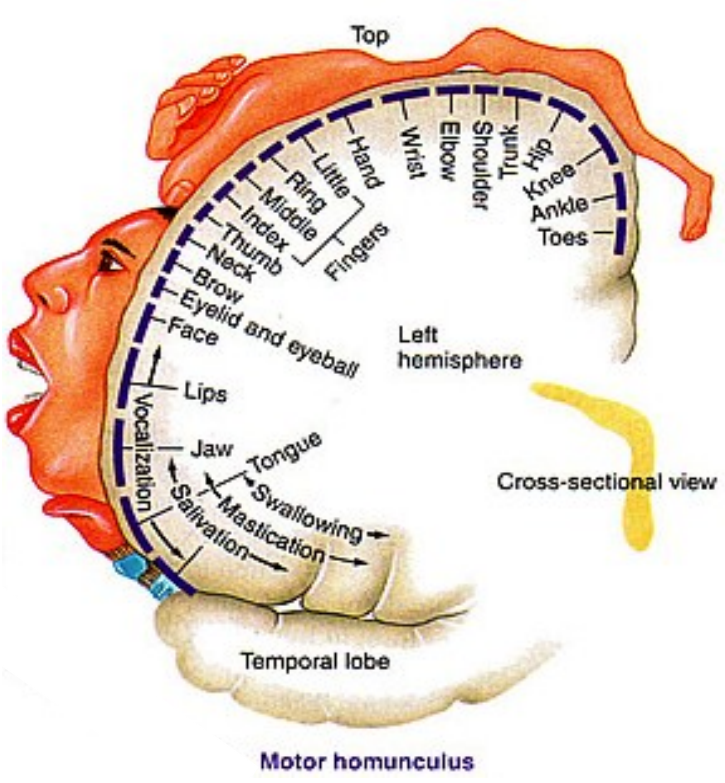

Figure 2.3 Motor homunculus illustration for the primary motor cortex to different parts of the body. Adapted from Sherwood (2011).

TES and TMS induce a MEP within a target muscle via different mechanisms (Di Lazzaro *et al.*, 1998). Di Lazzaro *et al*. (1998) investigated a descending volley from TMS in comparison to TES. It was concluded that at active motor threshold, MEPs from TES comprise predominantly of D-waves (direct waves), whilst MEP size was largely influenced by I-waves (indirect-waves) from TMS. The two types of waveform have different latencies as they represent different mechanisms for the descending action potential. The initial volley is called the D-wave because it directly activates the pyramidal tract neurons whilst the I-waves have a longer latency and indirectly activate the pyramidal tract neurons through the cortical interneurons (Awiszus and Feistner, 1994). It should be noted that TMS predominantly elicits MEPs indirectly via cortical interneurons, however direct activation of the pyramidal tract has been shown to occur under high intensity TMS outputs (Di Lazzaro *et al.*, 1998). For example, at TMS

intensities above active motor threshold, D-waves have been shown to occur. Furthermore, coil orientation (Di Lazzaro *et al.*, 1998) and the specific muscle under investigation influence how a MEP is elicited (Nielsen *et al.*, 1995; Di Lazzaro *et al.*, 1998).

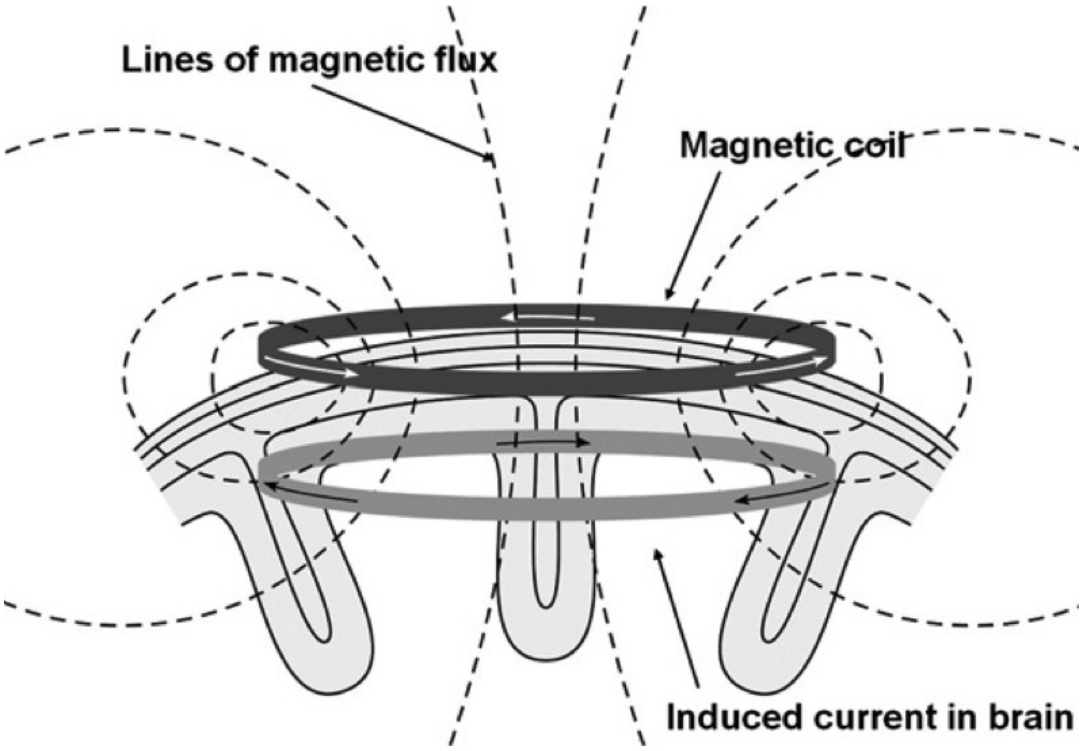

Figure 2.4 Illustration shows the direction of current from a circular magnetic coil and the induced current in the brain (Hallett, 2000).

With the increased use of TMS, different shaped coils have been designed for a variety of purposes. Circular coils have a relatively large output of 3.6 Tesla (Hovey and Jalinous, 2006), however, the ability to focus on a specific area of M1 is limited due to the large unfocussed field created. Whilst circular coils induce tissue current at near zero in the centre of the coil and maximally under the ring of the coil, double coned coils create a more focal magnetic field (Figure 2.5). Furthermore, an angled coil enhances the intensity of the coil in the centre and thus provides a useful tool to stimulate muscles of the lower limb that are more difficult to access with flat coils (Hovey and Jalinous, 2006). From magnetic stimulation of M1 a number of variables

are possible to ascertain, which include MEP size, motor threshold and the length of the silent period. These variables are described in the following paragraphs.

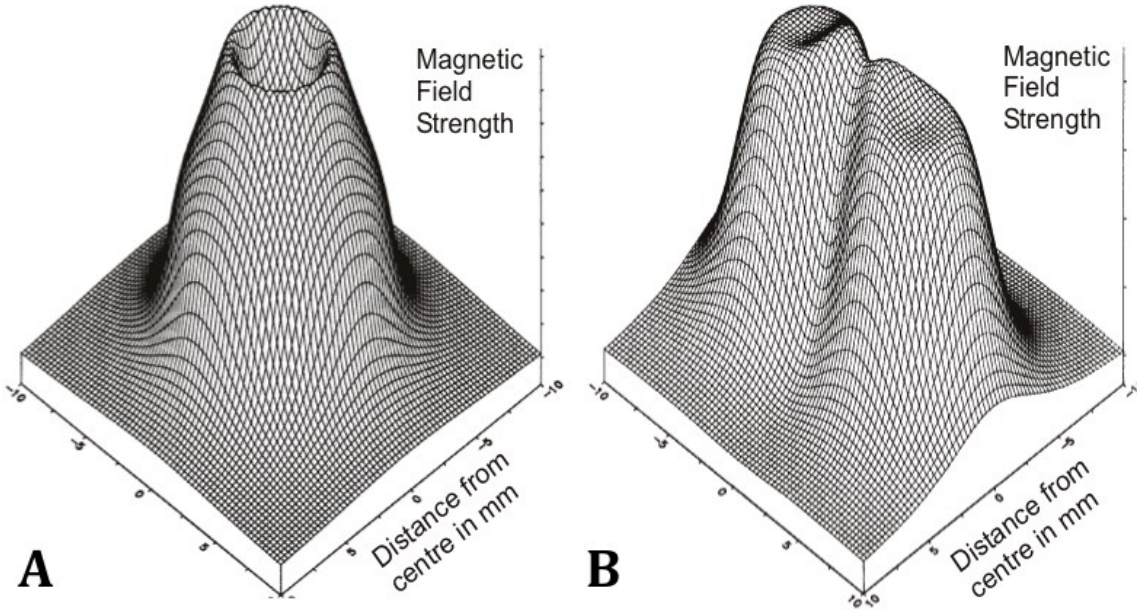

Figure 2.5 The magnetic field of a 90mm circular coil (**A**) and a double 70mm coil (**B**) (Hovey and Jalinous, 2006).

MEP is an action potential recorded at the muscle following stimulation of the primary motor cortex (Goodall *et al.*, 2014) and examines the balance between the excitability and inhibition along the brain to muscle pathway (Hallett, 2000). If the M1 is stimulated with TMS during an active, voluntary muscle contraction, a short period of EMG 'silence' is evident following the MEP (Figure 2.6). This is known as the silent period (Wilson *et al.*, 1993; Hallett, 2000). The latter part of the silent period is suggested to be influenced by cortical inhibition whilst the early part is considered to be spinal inhibition (Wilson *et al.*, 1993; Hallett, 2000). More specifically, the silent period is most likely mediated by gamma-aminobutyric acid (GABA) receptors situated within M1 (Werhahn *et al.*, 1999). Figure 2.6 shows an example of a representative trace of the silent period. Factors such as the intensity of contraction (Wilson *et al.*, 1993) and the

stimulus intensity (Saisanen *et al.*, 2008), can influence the length of the silent period. Both mathematical modelling and visually determining the silent period have been shown to be an effective measure to quantify the silent period (Damron *et al.*, 2008).

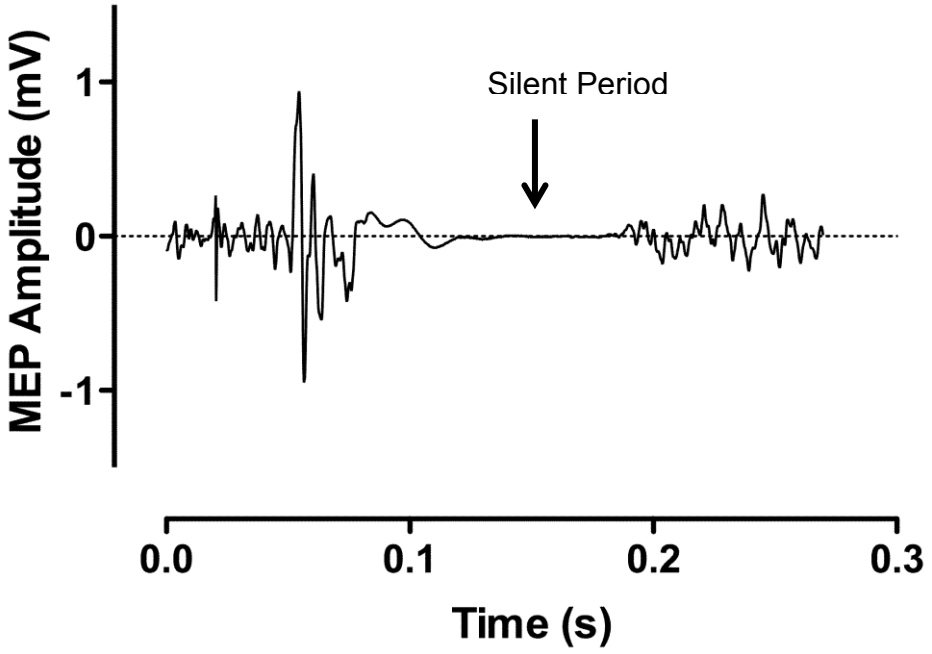

Figure 2.6 An example trace of the TMS elicited silent period.

Motor threshold represents membrane excitability of corticospinal and spinal neuromuscular neurons (Kobayashi and Pascual-Leone, 2003) and is defined as the lowest TMS output that evokes a response in the targeted peripheral muscle (Rossini and Rossi, 2007). Motor threshold is often conducted at rest, however a mild contraction is often used in some studies to establish an active motor threshold (Ziemann *et al.*, 1995; Tergau *et al.*, 2000). An MEP greater than 50 μV in 5 out of 10 pulses is commonly accepted as the resting motor threshold, (Rossini *et al.*, 1994; Kobayashi and Pascual-Leone, 2003).

Although the use of TMS to investigate the brain to muscle pathway has been extensive, relatively few have investigated the reliability of TMS responses. The reproducibility of TMS has been shown to be affected by small changes within the method (Kamen, 2004; Darling *et al.*, 2006; Malcolm *et al.*, 2006; van Hedel *et al.*, 2007) and the population under assessment (Wheaton *et al.*, 2009; Cacchio *et al.*, 2011), so it is critical to establish the repeatability of the measure and method used. For example, Darling *et al*. (2006) demonstrated that a mild contraction of 5 or 10% MVC stabilised the MEP response compared to rest. Additionally, the type of contraction (isometric versus dynamic) has also been shown to influence the repeatability of MEP amplitude and corticospinal silent period (van Hedel *et al.*, 2007). Whilst an isometric contraction provides a good model for examining neurological adaptations due to its repeatability, it lacks specificity to human movement.

2.3.2 Peripheral Nerve Stimulation (PNS)

Unlike TMS, PNS has been extensively used throughout the last century to investigate plasticity of the nervous system in research and clinical settings (Zehr, 2002; Knikou, 2008). There are numerous uses of PNS, one of the most common use of PNS in the exercise literature is to superimpose a relatively strong electrical pulse, during a maximal contraction to assess the activation of the muscle (Merton, 1954; Herbert and Gandevia, 1999). However, this section will focus on the role of the Hoffman reflex (H-reflex) and the V-wave in assessing spinal plasticity as the interpolated twitch technique does not give any indications of spinal adaptations.

The H-reflex takes its name from Paul Hoffmann, who originally described the spinal reflex in the early 1900's (Hoffmann, 1910). The H-reflex is a monosynaptic reflex of the Ia afferents (Knikou, 2008) and is a balance between motoneuron excitability and presynaptic inhibition of Ia afferent loop (Aagaard *et al.*, 2002). However, oligosynaptic

pathways appear to have an influence on the later part of the H-reflex (Burke *et al.*, 1984). As previously suggested by Aagaard (2003) it can therefore not be excluded that changes in the H-reflex pathway are influenced by postsynaptic inhibition of the Golgi Ib afferents. The H-reflex has been elicited in numerous upper and lower extremity muscles (For a detailed list see: Zehr, 2002). Briefly, the flexor carpi radialis is the most studied reflex in the upper limb, and the soleus is the most examined in the lower limb (Zehr, 2002).

The H-reflex is a stretch reflex that excludes muscle spinal discharge (Zehr, 2002). Figure 2.7 illustrates the neurophysiological pathway responsible for the H-reflex. The H-reflex requires low intensity, short duration electrical stimulation of the peripheral nerve. As Ia afferents have a smaller diameter than the α–motorneuron (Schieppati, 1987), a low level electrical impulse can discriminate between the Ia afferents and the α–motorneuron (Aagaard *et al.*, 2002). Once the Ia afferents are activated, action potentials travel toward the spinal cord, which activates the α–motorneurons that travel to the muscle; this response can be recorded at the muscle with surface EMG as the H-reflex. At higher PNS intensities, both Ia afferents and α–motorneurons are activated as the threshold is reached to activate the larger diameter α–motorneurons. With increasing intensity, α–motorneurons are directly activated rather than through the afferent volley, therefore the action potential travels from the site of nerve stimulation straight to the muscle producing an EMG response at the muscle termed the M-wave (Palmieri *et al.*, 2004). Consequently, the M-wave has a shorter latency then the H-reflex. For example, in the soleus the M-wave appears from approximately 0.006 s to 0.009 s, whilst the H-reflex is evident at around 0.03 s (Palmieri *et al.*, 2004). With increasing stimulation intensities, there are antidromic action potentials travelling along the α–motoneuron to the spinal cord. Antidromic collision occurs with the reflex that causes phase-out cancellation. Increasing electrical stimulation causes an increased H-reflex but also an increase in antidromic collision and thus at high electrical

stimulation intensities, the H-reflex is completely abolished (Aagaard, 2003). H-reflex is recorded as peak-to-peak amplitude and expressed relative to the maximal M-wave (M_{MAX}).

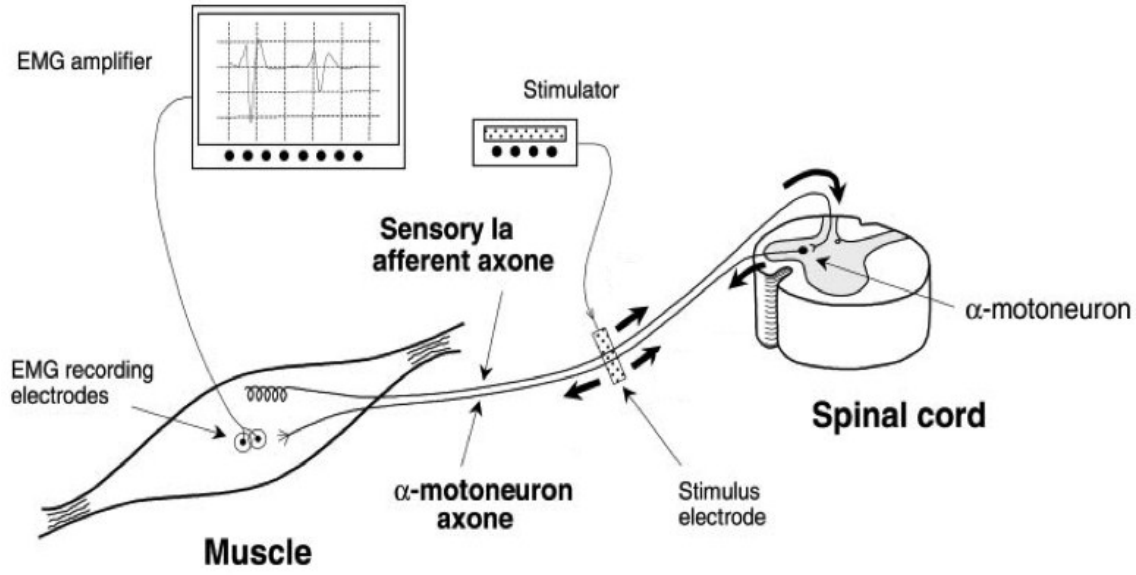

Figure 2.7 An illustration of the H-reflex pathway, adapted from Aagaard *et al*. (2002).

The V-wave is an EMG variant response of the H-reflex recorded during maximal voluntary contractions (Aagaard *et al.*, 2002). Figure 2.8 illustrates the neurophysiological pathway responsible for the V-wave. Supramaximal stimulation is applied to the peripheral nerve and similar to H-reflex, action potentials travel along the α–motorneurons to the muscle as an M-wave. Due to the antidromic collision from the simultaneous electrical stimulation of the Ia afferents and the α–motoneuron, the H-reflex is abolished. However, the descending drive causes a cancellation of the antidromic action potentials, therefore creating a pathway for an evoked reflex response that is termed the V-wave. The V-wave is reported as peak-to-peak and expressed relative to the M_{MAX}; an increased V-wave represents a global change in efferent motoneuron output during maximal muscle contractions (Aagaard *et al.*, 2002).

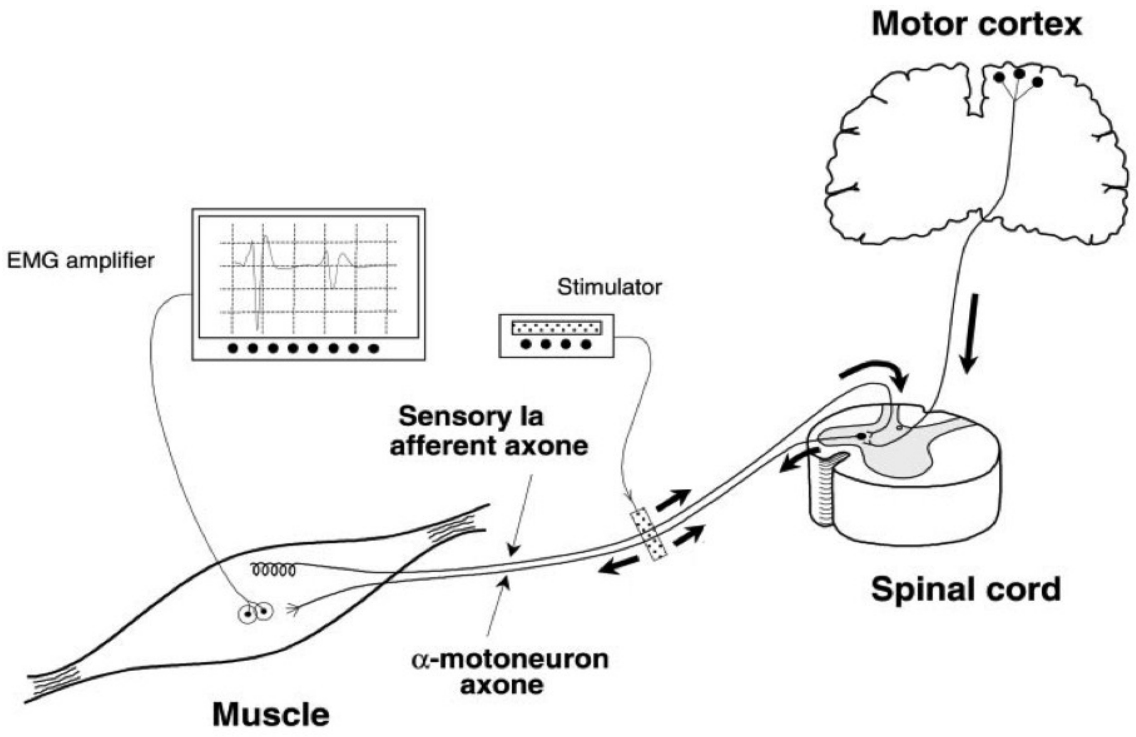

Figure 2.8 An illustration of the V-wave pathway adapted from Aagaard *et al*. (2002).

As the H-reflex technique is an established method for assessing spinal excitability, it is unsurprising that numerous studies have shown it is highly reproducible (Hwang, 2002; Christie *et al.*, 2004; Robertson and Koceja, 2004; Mynark, 2005; Chen *et al.*, 2010). Continually, intraclass correlations have been reported in excess of 0.9 for the soleus muscle (Robertson and Koceja, 2004; Mynark, 2005), however, in other muscles such as the quadriceps (Hopkins and Wagie, 2003) and the tibialis anterior responses are known to be less repeatable. Differences may be due to the accessibility of the peripheral nerve and/or other factures such as a change in muscle length (Simonsen and Dyhre-Poulsen, 2011) and the intensity of contraction (Chen *et al.*, 2010). Therefore, despite the H-reflex being an established and reliable method, any experimental study using dynamic muscle contraction that are not driven by the tibial nerve should initially establish the repeatability of the measure. Unlike the H-reflex, there is little research investigating the reliability of the V-wave (Solstad *et al.*, 2011; El

Bouse *et al.*, 2013). Whilst both these studies showed that the V-wave was a reliable measure, further research is warranted to establish the reproducibility in lower extremity muscles, such as the tibialis anterior.

2.4 Shortening and Lengthening Contractions

Since the late 19th century, shortening and lengthening muscle contractions have been studied (Chauveau, 1896). Shortening, or concentric, muscle contractions occur when the muscle's contractile apparatus shorten; whilst lengthening, or eccentric, muscle contractions occur as the muscle's contractile apparatus lengthen (Asmussen, 1953). Lengthening muscle contractions consist of resisting load or performing movements against gravity, and shortening muscle contractions are responsible for locomotion (Isner-Horobeti *et al.*, 2013). It has long been established that lengthening muscle contractions produce greater forces compared to shortening contractions (Doss and Karpovich, 1965; Westing and Seger, 1989; Westing *et al.*, 1991; Crenshaw *et al.*, 1995). Early reports have demonstrated up to an 80% higher force generating capacity of lengthening when compared to shortening muscle contractions (Rodgers and Berger, 1974), though smaller differences of 8% have also been reported (Aagaard *et al.*, 2000b). Another unique and advantageous characteristic of lengthening contractions is the lower metabolic cost when compared to the same absolute load (Okamoto *et al.*, 2006; Vallejo *et al.*, 2006).

2.4.1 Benefits of Lengthening Contractions

It is unsurprising that lengthening muscle contractions are a key part of rehabilitation and resistance training programmes for both clinical and athletic populations. More specifically, high intensity lengthening muscle contractions have shown to increase strength in Parkinson's patients (Hirsch *et al.*, 2003) and consequently improve

individual's ability in everyday tasks such as walking (Scandalis *et al.*, 2001). Lengthening resistance training contractions have also been shown to have a greater influence on strength changes in stroke patients when compared to shortening contractions (Engardt *et al.*, 1995). Furthermore, the addition of lengthening resistance training in an exercise programme augmented an increase in lean tissue in type II diabetes patients (Marcus *et al.*, 2008) and has even been shown to be an effective tool to increase strength in cardiovascular diseased patients (Meyer *et al.*, 2003). In an athletic population, a reduction in hamstring injuries has been shown in soccer players (Askling *et al.*, 2003) and an increase in the performance of dynamic movements (Clarka *et al.*, 2005) from a resistance training programme that included overloading lengthening contractions. Furthermore, lengthening contractions have been shown to reduce the risk of falls in the elderly (LaStayo *et al.*, 2003). Whilst this list is not exhaustive it provides a clear example of the use and benefit of lengthening contractions. The apparent superiority of lengthening muscle contractions to maximise rehabilitation and resistance training programmes may be due to their unique control strategies. Accordingly, this section of the review will discuss cortical, spinal and neuromuscular control strategies of lengthening muscle contractions.

2.4.2 Morphological Adaptations to Lengthening Contractions

In a traditional model (Sale, 1988), initial increases in strength are predominantly thought to be due to neurological adaptations (discussed in detail in section 2.5), whilst more longitudinal changes in strength are often a result of morphological changes at the muscle. Lengthening contractions have been suggested to be superior to shortening contractions at increasing the size of muscle (Hortobagyi *et al.*, 2000; Farthing and Chilibeck, 2003; Vikne *et al.*, 2006), however not all studies support this notion (Nickols-Richardson *et al.*, 2007; Reeves *et al.*, 2009).

Lengthening contractions have been shown to produce a greater muscular tension compared to shortening contractions and consequently have been suggested to provide a greater stimulus for hypertrophy (Roig *et al.*, 2009; Schoenfeld, 2010). This notion is further support when the speed of contraction is taken into consideration. Farthing (2003) has shown the greatest force producing capacity of the muscle was during fast lengthening contractions when compared to slow lengthening, and fast and slow shortening, contractions. Consequently, the greatest increase in the size of the muscle was seen following fast lengthening training, further supporting the theory that tension within the muscle is a significant contributor to changes in muscle size. However, absolute training load is not solely responsible for the greater gains in muscle size. When matched for absolute load rather than relative load, shortening resistance training has actually been shown to cause a greater gain in muscle size compared to lengthening resistance training (Mayhew *et al.*, 1995).

It has also been suggested that lengthening muscle contractions target type II muscle fibres during a resistance programme (Hortobagyi *et al.*, 2000). As type II muscle fibres are more susceptible to hypertrophy (Verdijk *et al.*, 2009), it is unsurprising lengthening contractions appear to show a greater increase in muscle size. Therefore, to maximise gains in muscle mass, lengthening contractions should be a major part of the resistance training programme.

2.4.3 Motor Control of Lengthening and Shortening Muscle Contractions

During voluntary contractions, there is a large body of evidence showing a lower surface EMG in lengthening compared to shortening muscle contractions (Tesch *et al.*, 1990; Amiridis *et al.*, 1996; Aagaard *et al.*, 2000b; Komi *et al.*, 2000; Pasquet *et al.*, 2000; Duclay *et al.*, 2011). This is despite a higher force producing capacity for lengthening muscle contractions (Westing and Seger, 1989; Westing *et al.*, 1991;

Crenshaw *et al.*, 1995). For a given force there is also a reduction in EMG and oxygen cost (Bigland-Ritchie and Woods, 1976) during lengthening contractions, indicating a more efficient contraction. Furthermore, the greater force twitch during lengthening MVCs further demonstrates unique neurological modulations during lengthening contractions (Löscher and Nordlund, 2002). This section will explore differences in the motor control of lengthening and shortening contractions at the muscle, spine, cervicomedullary and cerebellum.

2.4.3.1 Muscle

There is evidence to suggest that the recruitment order of motor units is altered during lengthening contractions (Nardone *et al.*, 1989; Howell *et al.*, 1995). Type II higher force motor units are selectively recruited in preference to type I lower force motor units (Nardone *et al.*, 1989; Howell *et al.*, 1995). Consequently, EMG activity is lower as fewer motor units are thought to be required for the same level of force; however, this is not a widely supported mechanism (Bawa and Jones, 1999; Stotz and Bawa, 2001; Pasquet *et al.*, 2006). The lower EMG values recorded lengthening compared to maximal shortening contractions, may be due to an increase inhibition during a lengthening muscle (Aagaard *et al.*, 2000b). Specifically, during a maximal lengthening contrition, Golgi organs excite the Ib afferents that activate inhibitory interneurons thus causing a reduction in muscle activity (Aagaard *et al.*, 2000b). It has been reported that the Golgi organs inhibit muscle activity to act as a protective mechanism during lengthening contraction (Tomberlin *et al.*, 1991), though the role the Golgi tendon organs have in protecting the muscle from damage is unclear (Chalmers, 2002). The increase inhibition suggested in a lengthening contractions is further supported from the use of the twitch-interpolation technique on shortening and lengthening maximal contraction. Whilst shortening maximal contractions have been shown to almost fully activate the motor pool, lengthening activates a smaller percentage of the pool (Westing *et al.*, 1990). Finally, synchronization may also influence the EMG signal; a

greater synchronization of motor units has been reported during lengthening muscle contractions when compared to shortening contractions (Semmler *et al.*, 2002). Theoretically, if there is a greater synchronisation to achieve the same level of force less drive is needed.

2.4.3.2 Spinal

In a rested state, a reduction in lengthening compared to shortening H-reflex amplitude have been demonstrated in numerous studies (Pinniger *et al.*, 2001; Nordlund *et al.*, 2002; Duclay and Martin, 2005). Specifically, an increased presynaptic inhibition and increased post activation depression have been reported as the specific mechanisms for reduction in the H-reflex during passive lengthening contractions (Hultborn *et al.*, 1987; Rudomin and Schmidt, 1999; Duclay and Martin, 2005). A reduction in H-reflex amplitude also appears evident during an active lengthening compared to shortening contraction (Duclay and Martin, 2005; Duclay *et al.*, 2011), with no change in V-waves (Duclay *et al.*, 2008; Hahn *et al.*, 2012). It should be noted that not all intensity contractions and muscles showed a reduction in H-reflex amplitude. Despite this, the information present here strongly suggests that supraspinal drive is inhibited at a spinal level during lengthening contractions and may be a mechanism for the reduced EMG evident at the muscle. As discussed earlier in this review, lengthening contractions generate a greater force compared to shortening contractions. Therefore, it is plausible to suggest that afferent feedback from the Golgi organs may contribute to the reduction of muscle activity recorded at the muscle during a lengthening contraction (Aagaard *et al.*, 2000b). Though, with no differences reported between isometric and lengthening MVC but a reduction in H-reflex shown (Duclay *et al.*, 2008; Duclay *et al.*, 2011), tension regulating mechanism from the Golgi organs may not contribute to the reduced spinal excitability and muscle activity during lengthening contractions. As the H-reflex is a Ia afferent reflex, presynaptic inhibition of the of the Ia afferents appears a more likely

mechanism in reducing EMG at the muscle during lengthening contractions (Duclay and Martin, 2005).

2.4.3.3 Cervicomedullary and Cerebellum

TMS (Löscher and Nordlund, 2002; Duclay *et al.*, 2011) and EEG (Fang *et al.*, 2001; Fang *et al.*, 2004) studies have investigated differences in motor control between lengthening and shortening muscle contractions at a cortical level. Fang *et al*. (2001) investigated movement related cortical potentials (MRCP) from EEG recordings during submaximal shortening and lengthening contractions. MRCP were higher during lengthening contractions. The authors concluded that lengthening contractions are processed and planned differently to shortening contractions, due to the complexity of the movement. Therefore, the greater MRCP might be a result of a greater cortical cost to process the amount of sensory feedback immediately prior and during lengthening muscle contractions (Fang et al., 2001); a result that was later confirmed (Fang *et al.*, 2004). On this evidence, it appears that despite the lower EMG recorded at the muscle and higher spinal inhibition discussed in the previous section, there is actually greater supraspinal activity during lengthening muscle contractions.

During maximal contractions, the majority of previous work has reported no difference in corticospinal excitability of lengthening and shortening muscle contractions (Löscher and Nordlund, 2002; Duclay *et al.*, 2011), though there is some evidence to suggest MEP's are reduced during lengthening contractions when recorded during MVC's (Duclay *et al.*, 2011). The reduction in corticospinal excitability appears more conclusive at submaximal contraction intensities (Abbruzzese *et al.*, 1994; Sekiguchi *et al.*, 2001), the exact mechanisms why, however, remain unclear. MEP's examine the balance between excitability and inhibition along the brain to muscle pathway (Hallett, 2000). Consequently, an increase in cortical excitability may occur but a heighted

spinal inhibition may reduce the EMG response at the muscle. To investigate this further, Gruber *et al*. (2009) used the MEP to cervicomedullary motor evoked potential (CMEP) ratio to determine the difference between control mechanisms of lengthening and isometric contractions at a cortical versus spinal level. When compared to isometric contractions, lengthening contractions CMEPs were lower, however the MEP/CMEP was unchanged. This information further suggests that there is a heightened cortical activity and spinal inhibition during lengthening compared to shortening contractions. Though recent evidence has shown contradictory finds with no change in CMEP during lengthening when compared to shortening contractions (Hahn *et al.*, 2012).

There appear clear neurological differences between shortening and lengthening muscle contractions along the brain to muscle pathway. How these are modified during resistance training programmes is unclear and will be discussed in section 2.8.

2.5 Acute Neurological Adaptations to Resistance Training

The plethora of literature investigating modifications in the nervous system from resistance training has lead to a number of reviews (Folland and Williams, 2007; Carroll *et al.*, 2011; Kidgell and Pearce, 2011). Whilst morphological adaptations cannot be excluded as a contributing mechanism for acute increases in strength from resistance training, the major increases in initial force are thought to arise from neurological adaptation (Sale, 1988; Gabriel *et al.*, 2006; Folland and Williams, 2007). Furthermore, acute increases in strength have been reported within days following a single strength based task or training (Kroll, 1963; Patten *et al.*, 2001), with neurological adaptations occurring 24 h post high intensity lengthening contractions (Dartnall *et al.*, 2008). Figure 2.9 shows the classic conceptual temporal characteristics of strength changes and the contribution of neurological and morphological

adaptations. This section of the review will discuss the neurological mechanisms responsible for the increase in force generating capacity of the muscle.

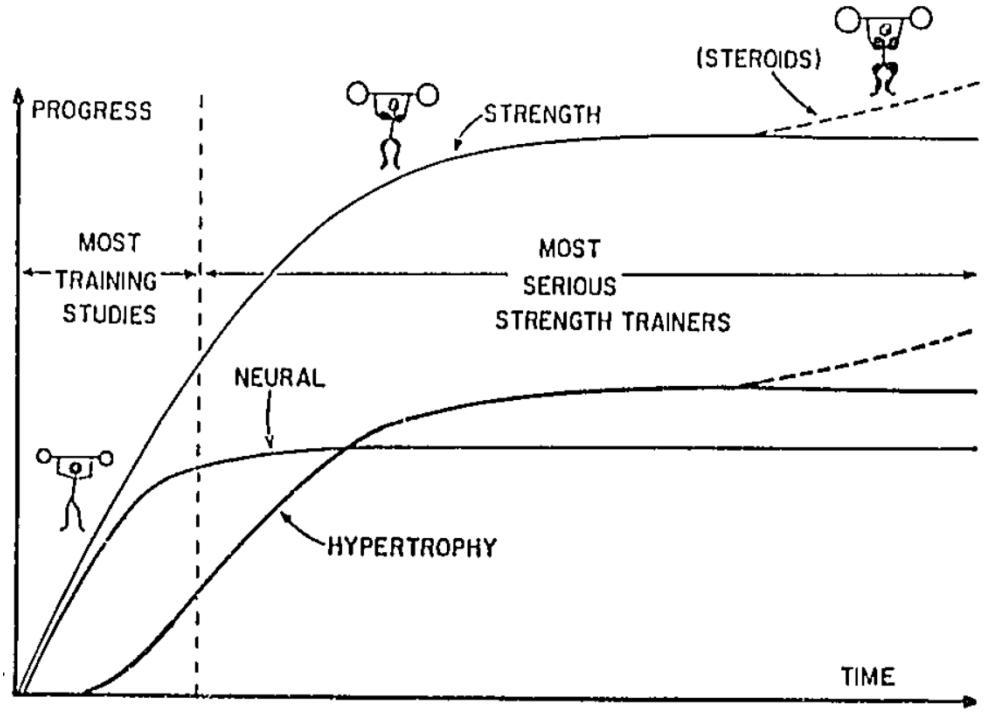

Figure 2.9 Illustration of the neural and morphological contribution to strength following resistance training (Sale, 1988).

2.5.1 Surface EMG

For over 50 years, there have been numerous examples of authors that used surface EMG to track the time course of neurological adaptations and strength from resistance training (Komi *et al.*, 1978; Moritani and deVries, 1979; Narici *et al.*, 1989; Hakkinen *et al.*, 1992; Hakkinen *et al.*, 1998; Rabita *et al.*, 2000). These studies showed an increase in strength and EMG, the authors conclude there is a heightened neural drive from the brain to the muscle pathway. For example, in one of the earlier studies Komi *et al*. (1978) used a 12 week isometric knee extension resistance training programme to investigate the neurological and morphological adaptations to resistance training.

Participants, on average, showed a 20% increase in isometric strength; this was independent of a change in cross-sectional area of the muscle. The increase in strength was accompanied with an increase in EMG activity. The authors also reported a reduced EMG/tension ratio at lower forces, suggesting a more efficient muscle contraction. Furthermore, a strong association between changes in force and EMG activity have also been shown across 8 weeks of resistance training (Hakkinen and Komi, 1983), with large increases of 50% EMG also shown (Yue and Cole, 1992).

Conversely, a number of studies have failed to show any increase in EMG activity following a resistance-training period (Carolan and Cafarelli, 1992; Keen *et al.*, 1994; Rich and Cafarelli, 2000). Despite technology improvements in recent years, in recording and analyzing EMG, non-significant results found in the literature may be due to the variability of the measure. The variability is affected by numerous issues, including electrode placement, data analysis, length of muscle, speed of contraction, temperature changes and skin preparation (Kamen and Caldwell, 1996; Farina *et al.*, 2004; Mathur *et al.*, 2005). Whilst variability may be reduced through ensuring the experimenter is methodically attentive, factors such as phase out cancellation during the fatigue state of muscle are more difficult to control (Keenan *et al.*, 2005). EMG can therefore provide a global measure of neurological adaptation; techniques such as fine wire and motoring changes in co-activation of the antagonist muscle have allowed a greater insight in to specific mechanisms responsible for the increase in strength. The use of these techniques will be subsequently discussed in the following sections.

2.5.2 Motor Unit Firing Frequency

There is growing support demonstrating an increase in motor unit firing frequency following resistance training (Patten *et al.*, 2001; Kamen and Knight, 2004; Pucci *et al.*, 2006; Christie and Kamen, 2010); however, the exact roll firing frequency has on

strength gains is unclear. Data suggests that increases in motor unit firing frequency are modified as early as 48 h from initial exposure (Patten *et al.*, 2001), despite no change in strength. However, after 42 days of resistance training, there was no change in motor unit firing frequency compared to baseline levels despite significant gains in strength (Patten *et al.*, 2001). Consequently, it seem logical to suggest that motor unit firing frequency plays an important role in motor control that may preside as long term strength adaptations, though increases in firing frequency do not appear to directly result in an increase in strength. Correlations between strength and motor unit frequency from groups of studies have also been reported as low as r^2 =0.15 (Carroll *et al.*, 2011). Both EMG and fine wire EMG assess a very small percentage of one muscle. Given that numerous muscles probably contribute to the increase MVC of individual contractions, it is unsurprising there are large discrepancies in the literature. However in various populations there are examples of increasing motor unit frequency and strength. For example older adults who have a history of resistance training have a greater motor unit firing frequency in the quadriceps (Leong *et al.*, 1999). It appears that whilst increases in motor unit firing frequency may contribute to increases in strength, both acutely and chronically, an increase in frequency does not equate to an increase in force generating capacity of the muscle.

2.5.3 Motor Unit Synchronisation

Motor unit synchronisation refers to the amount of simultaneous activity of action potentials (Sears and Stagg, 1976). Theoretically, if more muscle fibres are activated simultaneously, greater force or quicker rate of force can be applied. Computer stimulation show a positive relationship between an increase in motor unit synchronisation and increases in force (Yue *et al.*, 1995; Zhou and Rymer, 2004). Furthermore increased synchronisation has been shown in chronically resistance training individuals compared to untrained controls (Fling *et al.*, 2009), musicians (Semmler *et al.*, 2004) and in the dominant hand compared to the contralateral hand

(Semmler and Nordstrom, 1998). Whether an inherent part of the nervous system or a resistance training adaptation, is arguably difficult to ascertain with a between subject design. Early work (Milner-Brown *et al.*, 1975) indicated acute increases in strength within subjects are associated with an increase in motor synchronisation. Milner *et al*. (1975) showed a 128% increase in sychronisation after 6 weeks of resistance training. However, the methodology of the paper has since been criticised and results disputed (Yue *et al.*, 1995). Yue *et al*. (1995) concluded that when rectified, surface EMG cannot accurately identify the synchronisation from noise. More recent research has failed to show links between acute resistance training and motor unit synchronization (Kidgell *et al.*, 2006). Therefore, the exact contribution motor unit synchronization has to increase force generating capacity of the muscle from resistance training still remains to be determined.

2.5.4 Antagonist Co-activation

Little consistency exists in the literature as to the exact modifications in co-activation of the antagonist muscle that occurs following resistance training (Baratta *et al.*, 1988; Aagaard *et al.*, 2000a; Hakkinen *et al.*, 2000; Hakkinen *et al.*, 2001). Theoretically, a reduction in antagonist EMG should lead to an increase in force producing capacity of the agonist muscle. However, an increase in co-activation is an internal mechanism for the protection of connective tissue in order to maintain the integrity of the joint. For example, hamstring co-activation has been suggested to reduce the force imparted on the anterior cruciate ligament (Draganich and Vahey, 1990; Aagaard *et al.*, 2000a). Furthermore, co-activation is a key component in increasing vital components in force production such as limb stiffness (Milner and Cloutier, 1993). There are numerous logical explanations for the difference in findings amongst the literature. An increase in co-activation has been shown during maximal contractions compared to a reduction during submaximal contractions (Tillin *et al.*, 2011). Similarly, a reduced antagonist activity has been shown following only a week of resistance training (Carolan and

Cafarelli, 1992), suggesting improvements in motor control may be through changes in antagonist agonist activity. Finally, the variability of EMG in these studies cannot be ruled out as a reason for discrepancies in findings (Tillin *et al.*, 2011).

2.5.5 Acute Changes in Corticospinal Excitability

Surface EMG during an active muscle provides a relatively simple method for assessing modification in neural drive; however, it fails to distinguish between central and peripheral neurological adaptations. To further understand the site of neurological adaptations, research using EMG in conjunction with stimulation techniques could lead to a greater insight into the mechanisms responsible for the increase in acute strength.

An increasingly large body of research has used TMS to investigate changes in acute corticospinal adaptations to resistance training (Carroll *et al.*, 2002; Jensen *et al.*, 2005; Beck *et al.*, 2007; Griffin and Cafarelli, 2007; Kidgell and Pearce, 2010; Kidgell *et al.*, 2010; Weier *et al.*, 2012). More specificity, changes in MEP size and modulus have been used to investigate modifications in excitability and/or inhibition of the brain to muscle pathway. Despite the relatively large number of studies in recent years, it is difficult to draw definitive conclusions. For example, resistance training has shown a heightened corticospinal excitability through an increase (Beck *et al.*, 2007; Kidgell *et al.*, 2010; Weier *et al.*, 2012), decrease (Carroll *et al.*, 2002; Jensen *et al.*, 2005) and no change (Lee *et al.*, 2009; Kidgell and Pearce, 2010; Goodwill *et al.*, 2012; Latella *et al.*, 2012) in MEP amplitude. Increases in MEP amplitude have been suggested to be a result of an increase in the corticospinal excitability of neurons that innervate the target muscle via the spinal motorneurons (Kidgell *et al.*, 2010), arguably through an increased efficiency of corticospinal transmission (Kidgell and Pearce, 2011). Mechanisms such as an increased synchronisation of the action potential may also contribute to the increase in MEP amplitude (Semmler and Nordstrom, 1998; Griffin

and Cafarelli, 2007). Decreases in MEP amplitude found from previous work (Carroll *et al.*, 2002; Jensen *et al.*, 2005) would indicate a reduction in the activated motorneurons from the corticospinal derived action potential (Carroll *et al.*, 2002). Carroll *et al*. (2002) attributed the reduction in MEP amplitude during an active contraction to alterations in the firing rate of motorneurons. An increase in the hyperpolarisation of each motor unit causes the period of time when the motor unit is unable to stimulate the muscle fibre to reduce, and potentially decrease the MEP amplitude. Whilst Carroll *et al*. (2002) suggested adaptations were specific to the neurological mechanisms during an active muscle, Jensen *et al*. (2005) conversely found a decrease in MEP amplitude solely at rest and attributed the changes to a reduction in excitability along the corticospinal tract. The exact mechanistic changes that occur at a corticospinal level and induce an increase in maximal muscle force generating capacity remain to be determined. Numerous factors contribute to the lack of conformity found within the aforementioned studies. An increase in neuromuscular activation has been found in selective muscles of the quadriceps from isometric resistance training, with little change in others (Rabita *et al.*, 2000). A high inter-subject variation has also been shown with selective individuals appearing more susceptible to increases in EMG in certain muscles compared to others (Rabita *et al.*, 2000). Furthermore, muscle groups appear to react differently to TMS (Schieppati *et al.*, 1996) and thus may contribute to the lack of consistency found in the literature.

The different prescribed training programmes (load, volume, intensity and duration) and specifically the type of resistance training (ballistic versus non-ballistic) may further add to the inconsistencies in the findings reported in the literature and in some cases, it is difficult to determine the exact strength training protocols used in many of the studies. Often authors have failed to appropriately describe speed of repetition and how the resistance training programme was progressively overloaded, all of which appear key components in maximising neurological adaptations to resistance training (Kidgell *et*

al., 2010). Kidgell *et al*. (2010) suggested studies that employ high intensity resistance training or ballistic movements provide a novel stimulus that can cause adaptations in the CNS. For example, Weir *et al*. (2012) recently showed a large increase in strength from 4 weeks of barbell back squats at 80% of 1 RM. Participants in the study performed four sets of six to eight repetitions during each session with an increase in load of 2-5% on successful completion of six sets. This progressive and high load resistance programme was accompanied by an increase in resting corticospinal excitability. In agreement, Kidgell *et al*. (2010) performed the same resistance training programme and also found an increase in corticospinal excitability. Equally, isometric muscle contractions performed maximally appear to increase MEP's (Griffin and Cafarelli, 2007). Therefore, it would appear high load progressive resistance training above 80% of MVC is a vital component in increasing corticospinal excitability and supports Kidgell *et al*.'s (2010) supposition.

Movements that are performed with maximal velocity and acceleration are considered ballistic (Zehr and Sale, 1994). Even though absolute force is lower compared to the previously described resistance training protocols, contractions consisting of high force producing ballistic contractions cause comparable changes in MEP amplitude when compared to high load resistance training (Beck *et al.*, 2007). Greatest shifts from TMS-induced twitch force vectors have been seen following ballistic and high forced sustained contractions (Selvanayagam *et al.*, 2011), with lower contraction intensities showing no change (Classen *et al.*, 1998). This further emphasises the importance that, to ensure CNS adaptations are achieved, resistance training should be conducted under high intensity contractions, and may account for some of the inconstancies in the literature. However, it should be noted that improvements in muscle function have been shown following sustained contractions as low as 20% MVC (Laidlaw *et al.*, 1999). Laidlaw *et al*. (1999) showed an increase in MVC and an improvement in steadiness of contractions that was associated with a reduction in EMG. Therefore the intensity of

contraction used in the resistance-training programme cannot be the sole reason for the discrepancies found in MEP amplitude post resistance training.

The methodology used to record the MEP cannot be excluded as a reason for the reported difference in the resistance training literature. It is difficult to compare studies that have shown changes in excitability at rest to those that have shown no significant differences during an active muscle contraction. Beck *et al*. (2007) recorded MEP's under the same specific conditions that the training was performed at and reported large increases in MEP amplitude, indicating a possible task specific adaptation. However, research to date has failed to appropriately address this hypothesis. Further investigation into task specific, or even muscle contraction specific, adaptions in resistance training may further explain the differences found within the body of research.

No study has been identified that demonstrates a correlation between an increase strength and change in MEP amplitude and hence, the relationship and relevance of changes in corticospinal excitability have in resistance training are not entirely clear. Griffin and Cafarelli (2007) reported an increase in MEP amplitude after six days of resistance training. Despite MVC continuing to increase throughout the resistance training protocol, MEP amplitude plateaued. One hypothesis is the increase in MEP may be due to improved motor learning, rather than a direct result of resistance exercise. Improvements in skill have been shown in parallel with increase corticospinal excitability (Pascual-Leone *et al.*, 1995; Pearce and Kidgell, 2009) and may be a crucial adaptation in the improved performance/efficiency on a movement task (Jensen *et al.*, 2005). Furthermore, Muellbacher *et al*. (2001) showed that once a movement was learnt MEPs returned to baseline levels, despite an increase in strength from a single session. Distinguishing between skill acquisition and resistance training

adaptations is difficult because of the inclusion of unaccustomed movements in the resistance-training programme, however, few authors have attempted to answer this question.

Skill training causes specific reorganisation of movement representations (Remple *et al.*, 2001). Remple *et al*. (2001) examined the cortical representation of rats in a power reaching task and control task. The power-reaching rats were required to break progressively larger bundles of dried pasta to mimic resistance training, whilst the non power-reaching rats broke a single strand of pasta. Results indicated that the changes in the cortical representation were similar between groups, despite the power-reaching rats needing to apply high amounts of force to complete the task. However, increased excitatory synapse expression onto the spinal motor neurons was highest in the resistance-training group, suggesting spinal adaptation may be due to strength changes and cortical adaptation are predominantly involved in movement acquisition. Jensen *et al*. (2005) has also shown an increase cortical excitability following skill training, whilst a reduction in corticospinal excitability was shown in the resistance trained group. Furthermore, studies have shown increased cortical activity following the intervention of a skilled-based task (Karni *et al.*, 1995; Hund-Georgiadis and von Cramon, 1999), supporting the suggestion that movement/skill acquisition resides predominantly at a cortical level. Further research assessing neurological adaptations at multiple levels may support or refute this notion.

2.5.6 Acute Changes in Silent Period

Monitoring MEP's gives a global net change of excitory and inhibitory influences. The corticospinal silent period represents both spinal and intracortical inhibition (Wilson *et al.*, 1993), the length of which appears to be modified by the GABA-B receptor (Werhahn *et al*., 1999). Specifically, a reduction in the early part of the silent period is

suggested to be of spinal origin and the latter part cortical (Fuhr *et al.*, 1991; Inghilleri *et al.*, 1993; Uncini *et al.*, 1993; Ziemann *et al.*, 1993). Investigating changes in both MEP amplitude and the silent period length allows a greater insight into not only the mechanism responsible for the increase force generating capacity of the muscle, but also the mechanisms behind any such change in MEP amplitude. In recent years, a selected few studies have investigated changes in corticospinal inhibition following resistance training (Kidgell and Pearce, 2010; Kidgell *et al.*, 2010; Latella *et al.*, 2012). Studies using single pulse TMS following resistance training have shown both a reduction in the corticospinal silent period (Kidgell and Pearce, 2010; Latella *et al.*, 2012) and no change (Kidgell *et al.*, 2010). However, with only a few studies investigating changes in the corticospinal silent period, it is difficult to conclude with any certainty the existence of the reduction in corticospinal inhibition. Additionally, inconsistencies exist as to the exact influence the corticospinal silent period has on MEP amplitude. Kidgell and Pearce (2010) showed a reduction in the silent period and no change in MEP amplitude, whilst Kidgell *et al*. (2010) found an increase in MEP amplitude and no change in the silent period. Pair-pulsed TMS has provided a greater insight into changes in inhibition along the corticospinal tract following resistance training (Weier *et al.*, 2012). Short-interval intracortical inhibition (SICI) is believed to occur at a motor cortical level (Di Lazzaro *et al.*, 1998), predominantly influenced by the GABA-B receptor (Di Lazzaro *et al.*, 2000). Weir *et al*. (2012) has recently shown a reduction in SICI following 4 weeks of resistance training. The authors attributed the increase in strength to a release of the cortical representation from inhibition and focus of subsequent excitatory drive to produce the intended movement. However, given the relatively few studies, it is difficult to determine the exact role inhibition has on strength increases.

Even though not mutually exclusive, it is unclear if an increase in force generating capacity or movement acquisitions is a result of a reduction in corticospinal inhibition.

Using paired-pulse TMS, a reduction in SICI has been shown following skill training (Smyth *et al.*, 2010). Additionally, pharmacological interventions have linked a reduction in GABA inhibition from skill acquisition (Butefisch *et al.*, 2000; Lech *et al.*, 2001). Increasing the frequency of an already learnt task causes an increase in motor output, however, a greater cortical modification has been shown when the same task is unfamiliar to the individual (Pascual-Leone *et al.*, 1995). Therefore, it is vital to fully familiarise participants with the assessment task.

2.5.7 Acute Changes in Spinal Excitability and/or Inhibition

Changes in spinal excitability have been monitored using the H-reflex for numerous years. Initially, spinal modification has been compared in chronically resistance trained and untrained individuals (Milner-Brown *et al.*, 1975; Upton and Radford, 1975). However, this section will focus on acute changes in spinal excitability, chronic modifications will be discussed in greater detail in section 2.6.2. Aagaard *et al*. (2002) classically investigated the effects of 14 weeks acute resistance training on changes in spinal excitability (H-reflex). The authors found a 19% increase in H-reflex amplitude of the soleus muscle. The authors attribute the increase in strength to an improved transmission efficacy of the Ia afferent reflex. Interestingly, increases in H-reflex were only evident during maximal contractions, with no changes reported in H-reflex evoked at rest. Of the numerous resistance training studies investigating modification in spinal excitability since Aagaard *et al.* (2002), no single study has shown a change in H-reflex at rest (Scaglioni *et al.*, 2002; Del Balso and Cafarelli, 2007; Holtermann *et al.*, 2007; Fimland *et al.*, 2009a; Ekblom, 2010). Assessing the H-reflex during rest gives a less functional representation of changes in Ia afferent efficiency compared to during an active state (Aagaard *et al.*, 2002). Therefore, assessment of the H-reflex at is not a suitable assessment of changes in spinal excitability and/or inhibition. There appears little continuity to the exact changes in spinal excitability during an active muscle contraction. Numerous studies have shown an increase in H-reflex during active

muscles contractions (Aagaard *et al.*, 2002; Lagerquist *et al.*, 2006; Holtermann *et al.*, 2007; Duclay *et al.*, 2008) whilst others have shown little change (Beck *et al.*, 2007; Del Balso and Cafarelli, 2007; Fimland *et al.*, 2009a; Ekblom, 2010; Vila-Cha *et al.*, 2012). There appears no obvious trend or explanation for the different findings between studies. Increases in H-reflex have been shown at low to high contraction intensities, during dynamic and isometric resistance exercise. Furthermore, the magnitudes of strength gains seem to have little impact on changes in excitability. Studies showing large gains in strength of 44% (Fimland *et al.*, 2009a) have found little change in H-reflex, whilst relatively large changes in spinal excitability (19%) have been shown in smaller gains in strength (20%) (Aagaard *et al.*, 2002).

V-wave responses have shown a more consistent increase following resistance training (Sale *et al.*, 1983a; Aagaard *et al.*, 2002; Gondin *et al.*, 2006a; Del Balso and Cafarelli, 2007; Duclay *et al.*, 2008; Fimland *et al.*, 2009a; Fimland *et al.*, 2009c; Ekblom, 2010; Vila-Cha *et al.*, 2012), despite early work showing no change in V-waves evoked in thumb adductors (Sale *et al.*, 1982). As discussed in section 2.3.2, the V-wave reflects an increase in volitional drive from M1 (Aagaard *et al.*, 2002). Supraspinal activation of the motoneurons will in part cancel out the antidromic action potential thus allowing the spinal reflex to present at the muscle in the form of a V-wave (Aagaard *et al.*, 2002). Isometric resistance training has been shown to increase V-wave when assessed under the same conditions as training (Aagaard *et al.*, 2002). Additionally, dynamic resistance training has also been shown to increase V-wave using single joint isometric assessment (Fimland *et al.*, 2009a) and therefore it appears that increased volitional drive is transferable across tasks.

2.6 Chronic Neurological Adaptations to Resistance Training

Compared to the large volume of literature investigating acute neurological adaptations to resistance, little has focused on investigating how the nervous is modulated in already resistance-trained individuals. Individuals competing in weight category sports show large increases in strength from chronic resistance training with little change in muscle mass. Additionally, how the neurological system supports an increase in muscle mass is unknown. This section will discuss the limited research on neurological adaptations in chronic resistance trained individuals.

2.6.1 Corticospinal

A heightened corticospinal excitability has been shown in highly skilled racquet sport athletes, compared to social players (Pearce *et al.*, 2000), thus suggesting a continual modification of the CNS from years of training. As discussed earlier, it is well established that the primary M1 is a major influence in the early stages of resistance training. Whether this is due to an improved motor control or a greater capability of the nervous system to increase the force generating capacity of the muscle is unknown. Only isolated studies have provided data past the initial few weeks of resistance training to investigate chronic adaptations that reside in the nervous system.

Only one study has used TMS to investigate changes in corticospinal excitability in chronically resistance-trained individuals. Fernandez del Olmo *et al*. (2006) compared the TMS response in the biceps brachii of individuals who had a resistance training history of more than 2 years and individuals who have never participated in resistance training. No significant differences were found in MEP amplitude at contraction intensities between 10 and 90% of MVC. There was, however, a smaller evoked twitch during a maximal contraction in the resistance trained individuals. The authors

speculated that these were attributed the differences to increase voluntary activation of motor units and/or increase discharge rate. Further research is therefore needed in this area and will increase our understanding of the long-term neurological adaptations to resistance training. It may also provide greater clarity into the role of corticospinal excitability in early skill and resistance training programmes.

2.6.2 Corticospinal Variability

Cortical fluctuations that project onto spinal motorneurons are believed to cause stimuli-to-stimuli variability (Ellaway *et al.*, 1998). Acute adaptations from high intensity resistance training has shown greater stability of force during maximal contractions (Smits-Engelsman *et al.*, 2008). Furthermore, in older adults an improvement of submaximal force control has been shown following resistance training (Hortobágyi *et al.*, 2001). It appears evident that resistance training not only increases the force generating capacity of the muscle but also improves stability and control of the muscle. How the neurological system supports the improved motor control is unknown. One possibility is a reduced corticospinal variability (MEP variability). However, this has currently not been explored in the literature. Additionally, resistance trained individuals acquire numerous motor programmes through often complex resisted movements. If retrieving and adapting an existing motor programme is associated with a more rapid increase on an unfamiliar motor programme (Wise *et al.*, 1998), then theoretically resistance trained individuals may demonstrate a reduce corticospinal variability following a familiarisation session.

2.6.3 Spinal Excitability

At a spinal level, both H-reflex and V-waves have been compared in resistance trained and untrained individuals. An increase in V-wave has been evident in weightlifters'

hands (Milner-Brown *et al.*, 1975) and in elite sprinter's legs (Upton and Radford, 1975), indicating an increase in cortical drive and/or decreased inhibition to the descending muscle (Aagaard, 2003).

Unlike the V-wave, the H-reflex amplitude appears dependant on an individual's chronic training history. In athletes competing in power-based sports, data have been reported showing a decrease in amplitude compared to untrained individuals (Casabona *et al.*, 1990) and dancers (Nielsen *et al.*, 1993). Similarly, a larger H-reflex has been reported in endurance-based athletes compared to resistance-trained power athletes (Rochcongar *et al.*, 1979). Reflex twitch responses appear to show a similar trend to the EMG data with greater force produced from a maximal H-reflex in endurance trained individuals compared to power-based athletes (Maffiuletti *et al.*, 2001). Differences in spinal excitability between the athlete populations may be altered by a shift in muscle fibre type. Power-trained athletes have demonstrated a shift towards type II fibres (Clarkson *et al.*, 1980); type II fibres are less excitable than type I fibres in the Ia afferent volley (Almeida-Silveira *et al.*, 1996). Even though a shift in fibre type from chronic aerobic/anaerobic training appears a logical assumption for modifications in H-reflex, the genetically predetermined efficiency of the afferent reflex cannot be excluded. Logically, research has focused on specific muscles that have been exposed to the training stimulus. For example, the soleus and gastrocnemius are involved in the locomotion of running and thus shifts in H-reflex may be expected. Whether similar adaptations occur in lesser-trained muscle, that may not have a large shift in muscle fibre distribution, is unknown.

Despite resistance training and human locomotion consisting of both shortening and lengthening muscle contractions, all previous research investigating chronic adaptations have been conducted under isometric conditions. Sedentary individuals

have demonstrated an increase in tension regulating mechanisms during lengthening muscle contractions compared to a group of international athletes (Amiridis *et al.*, 1996). In this study by Amiridis *et al*. (1996) a reduced co-activation was evident in the athletes compared to sedentary individuals, demonstrating in untrained individuals there is neurological protective mechanisms to reduce absolute load and consequently tension the muscle is exposed to. Interestingly, no significant differences were reported during shortening muscle contractions. Therefore, chronic neurological adaptations should be assessed under changing muscle contractions to reveal task-specific adaptations from chronic resistance training exposure.

2.7 Shortening and Lengthening Resistance Training

Over a hundred years have past since initial descriptions of lengthening and shortening contractions (Chauveau, 1896). Understanding how to maximise these adaptations is crucial for rehabilitation in clinical conditions and enhancing sporting performance (Isner-Horobeti *et al.*, 2013). Despite the large quantity of studies investigating neurological and morphological adaptations following acute and chronic training with shortening and lengthening muscle contractions, the exact mechanisms for the increase in strength are not well understood. This section of the review will initially focus on differences in force changes between shortening and lengthening resistance training; and secondly, discuss the neurological mechanisms for increases in force.

2.7.1 Strength Changes from Shortening and Lengthening Muscle Contractions

Shortening and lengthening resistance training programmes have focused on training up to 25 weeks (Nickols-Richardson *et al.*, 2007), in muscles ranging from the elbow flexors (Farthing and Chilibeck, 2003), knee extensors (Duncan *et al.*, 1989), rotator cuffs (Mont *et al.*, 1994) and ankle evertors (Collado *et al.*, 2010). Contraction intensity,

volume, duration and population under investigation all influence the findings of individual studies. However, despite the multiple variables to take into consideration, there are distinct trends in the literature.

Consistently, studies have shown evidence of contraction specific increases in strength (Tomberlin *et al.*, 1991; Higbie *et al.*, 1996; Hortobagyi *et al.*, 1996; Seger *et al.*, 1998; Seger and Thorstensson, 2005; Miller *et al.*, 2006). There is also evidence of a superior increase in strength from lengthening resistance training. Hortobágyi *et al*. (1996) showed a 3.5 times greater increase in lengthening strength from lengthening resistance training compared to shortening. More recently, Miller *et al*. (2006) used sedentary women to compare shortening and lengthening resistance training. Lengthening resistance training was again shown to increase lengthening strength more, compared to shortening resistance training. Furthermore, lengthening resistance training improved shortening maximal strength to a similar degree as shortening resistance training. One suggestion is that lengthening resistance training is conducted at high absolute forces compared to shortening resistance training (Westing *et al.*, 1991; Crenshaw *et al.*, 1995), providing a greater stimulus and hence larger gains in strength from lengthening resistance training. However, there are numerous examples of studies showing no difference in strength gains when shortening resistance training is compared to lengthening (Tomberlin *et al.*, 1991; Mont *et al.*, 1994; Ben-Sira *et al.*, 1995; Seger and Thorstensson, 2005). Some studies have even shown a bias for shortening contractions (Ellenbecker *et al.*, 1988; Mont *et al.*, 1994). With training days per week, training intensity, muscle under investigation, population, duration of training period and subject numbers all vastly different in each individual study, discrepancies in the literature are to be expected.

A recent meta analysis (Roig *et al.*, 2009) showed a greater increase in lengthening strength from lengthening resistance training, though there was a trend towards a greater increase in shortening strength from shortening compared to lengthening resistance training, this was not significant. Furthermore, Roig *et al*. (2009) showed that lengthening resistance training had a greater influence on shortening strength than shortening resistance training has on lengthening strength which supports numerous studies (Hortobagyi *et al.*, 1996; Vikne *et al.*, 2006). Additionally, greater gains in total strength were found with lengthening resistance training (total percentage increase in lengthening and shortening MVC). However, the speed of contraction in training appears to greatly influence the magnitude of shortening and lengthening strength gains and could explain some of the different findings.

Lengthening contractions have been shown to produce larger forces with increasing velocities, whilst shortening contractions show a decrease in maximal force during higher velocity muscle contractions (Westing *et al.*, 1991). It is therefore logical to suggest that velocity of the contraction could have a significant influence on increases in strength. Training at high lengthening velocities will provide a greater stress on the muscle and conceivably a larger stimulus for an increase in strength. Supporting this notion, larger increases in lengthening strength from lengthening training occurring with fast velocity lengthening contractions has been shown (Paddon-Jones *et al.*, 2001; Farthing and Chilibeck, 2003). Velocity may also play a crucial part in the strength increase across contraction types; fast lengthening muscle contractions show a great transfer of strength across contraction types (Farthing and Chilibeck, 2003). It should be noted that there is evidence to suggest with increased velocities during lengthening contractions there is a decrease in force producing capacity of the muscle (Mayer *et al.*, 1994). Therefore, the suggested greater increase in strength from lengthening contractions may not be due to the greater stimulus through a larger absolute training load. Differences between strength gains from shortening and lengthening resistance

training may reside from unique neurological modification along the brain to muscle pathway. However there is only limited data in this area (discussed in section 2.8). Understanding the neurological adaptations of shortening and lengthening resistance training may explain some the discrepancies shown in strength gains of the respective contractions.

2.8 Neurological Adaptations to Shortening and Lengthening Muscle Contractions

As discussed previously in section 2.4.2, control strategies of lengthening and shortening muscle contractions differ from the motor cortex to the muscle (Duchateau and Enoka, 2008). Given the pool of literature investigating the neurological differences between shortening and lengthening muscles, it is surprising that relatively few studies have investigated nervous system adaptations from lengthening and shortening contractions, particularly at multiple levels of the CNS. Accordingly, this section of the review will discuss neurological adaptations from shortening and lengthening contractions, with particular emphasis on contraction/task specific neurological adaptations.

Hortobagyi *et al*. (1996) showed a 3.5-fold increase in strength that was accompanied by a 7-fold increase in EMG. The large increase in strength was attributed to a greater recruitment (from the CNS) of type II muscle fibres. Further evidence has also reported a preferential recruitment of type II muscle fibre during lengthening contractions (Nardone *et al.*, 1989). Whilst Hortobagyi *et al*. (1996) showed an increase in neurological drive from lengthening resistance training, Seger and Thorstensson (2005) failed to detect differences in EMG between shortening and lengthening resistance post resistance training. The authors concluded that the low subject numbers of five in each group contributed to the lack of findings. The participants in the study were also

described as ‘moderately trained’. Trained individuals have been shown to have a lower superimposed twitch force compared to untrained individuals (Amiridis *et al.*, 1996), suggesting a reduction in the neural inhibitory safety regulatory measures (Webber and Kriellaars, 1997; Aagaard *et al.*, 2000b). Even though Higbe *et al*. (1996) found a significant increase in EMG from pre to post training in both the shortening and the lengthening muscle contractions, there was no difference in post training EMG between groups.

The aforementioned studies use independent groups to assess differences between shortening and lengthening resistance. Aagaard *et al*. (2000b) exposed 15 individuals to 14 weeks of both shortening and lengthening resistance training to compare the neurological adaptations during shortening and lengthening contractions. As expected, lengthening and shortening force generating capacity increased. Interestingly, the average EMG response for the slow and fast lengthening contractions increased on average when compared to slow and fast shortening contractions. The training performed in the study was heavy dynamic exercises such as back squats. Whilst the study provides evidence of greater neurological adaptations from lengthening resistance training, the role shortening resistance training has on lengthening neurological adaptations cannot be ignored. Aagaard *et al*. (2000b) could not exclude the notion that gains in lengthening resistance training may be a result of selective recruitment of type II muscle fibres.

Variability of EMG may play a significant role in the lack of significant findings in some studies. For example, Blazevich *et al*. (2008) did not detect any changes in EMG pre to post and post to detraining, in shortening or lengthening training groups despite changes in the rate of force development (RFD) and MVC. Whilst experimenters make every effort to reduce variability, the nature of EMG can make detecting changes

difficult. Factors such as phase out cancellation and high within-subject variability may account for the lack of significant findings and consistency in the literature (Farina *et al.*, 2004). Assessing adaptation during a dynamic muscle contraction further adds to the potential variability of testing. Interference of EMG signals recorded at the muscle belly are highly susceptible to small muscle movements (Rainoldi *et al.*, 2000) as the skin slides over the muscle. Future research using dynamic muscle contraction should initially establish a reproducible protocol and establish the error of measurement when using EMG. Therefore, the first experimental study in this thesis will establish the reliability of a protocol using EMG during shortening and lengthening contractions.

The signal from Surface EMG whilst a muscle is active provides a global measure of changes in the nervous system. As TMS and PNS assess the neurological system from a corticospinal and spinal level, using these techniques will provide a more comprehensive assessment of CNS adaptation and consequently increase our understanding of how lengthening and shortening resistance training increases force. Little research has used these techniques to investigate how the CNS adapts to lengthening resistance training (Duclay *et al.*, 2008; Ekblom, 2010) and no study has used these methods to assess differences in strength increases from lengthening and shortening resistance training.

Recently, lengthening contractions have been coupled with shortening contractions in a dynamic task to investigate the effects on volitional drive and spinal excitability (Ekblom, 2010). Participants performed calf raises using a Smith machine to raise (Shortening) and lower (lengthening) themselves up and down, respectively. No differences were found in H-reflex during rest or high intensity muscle contractions (H_{SUP}), although an increase in V-wave was evident during shortening and lengthening contractions (Ekblom, 2010). In this study (Ekblom, 2010) it was difficult to delineate

the influence that lengthening muscle resistance training had on adaptations to the nervous system because the training was coupled with shortening contractions; furthermore, subjects were not trained on the same task they were assessed with. Despite this limitation, there was a clear transfer between the training and assessment tasks, although it seems intuitive to suggest that the magnitude of adaptation may be underestimated given the lack of task specificity between the training and assessment activities.

Only one study has appropriately addressed these limitations. Duclay *et al*. (2008) used PNS to investigate the effect of solely lengthening resistance training on H-reflex and V-wave during lengthening and shortening muscle contractions. H-reflex and V-wave were assessed in the soleus and medial gastrocnemius with differing results. No changes were found in the resting H-reflex regardless of muscle contraction, however in contrast, an increase in H_{SUP} was found. This was evident during lengthening, shortening and isometric muscle contractions in the medial gastrocnemius but only during lengthening in the soleus. The lack of differences between the two studies (Duclay *et al.*, 2008; Ekblom, 2010) may be due to the lack of training specificity to the conditions H_{SUP} was assessed under. Ekblom (2010) performed dynamic resistance training whilst the assessment was conducted on an isokinetic dynamometer so arguably had less transfer compared to Duclay *et al*. (2008), who conducted training and assessment on the isokinetic dynamometer. Furthermore, a faster angular velocity was used by Duclay *et al*. (2008) (20°/s) compared to (5°/s) by Ekblom (2010). Ekblom (2010) suggested that the increased velocity used by Duclay *et al*. (2008) allows for a greater potential to reduce presynaptic inhibition. However, there is little change in EMG activity during increasing lengthening velocities (Christou *et al.*, 2003) suggesting that modification of spinal inhibition may be minimal. An increase in V-wave was also found post resistance training in all muscle contractions and in both muscles, apart from during maximal shortening muscle contractions (Duclay *et al.*, 2008). The data

suggested that increased maximal force during lengthening muscle contractions may be due to an enhanced supraspinal volitional drive and increased excitability/reduced pre-synaptic and post-synaptic spinal inhibition. Differences in findings between muscles within the same study (Duclay *et al.*, 2008) may be due to the specific neural mechanisms that influence spinal excitability of each muscle (Meunier and Pierrot-Deseilligny, 1998).

The work by Duclay *et al*. (2008) appears to be the only study that has assessed the dependent variables during the same task as the training. The study offers a unique insight into how lengthening muscle contractions modulate the nervous system on specific lengthening contractions and transfer across contraction types; however it fails to address numerous issues. For example, it is unknown if there is a similar transfer of spinal excitability and/or volitional drive from shortening resistance training to lengthening muscle contractions or lengthening resistance training to shortening muscle contractions. Thus, future research should investigate spinal neurological adaptations across from shortening and lengthening resistance training.

2.9 Detraining

Detraining can be described as partial or complete loss of training induced adaptation (Mujika and Padilla, 2000). For resistance training, this would be a decrease in maximal force generating capacity of the muscle as a result of morphological and neurological degradation. This section of the review will firstly discuss the loss of strength following the cessation of resistance training and the potential neurological mechanisms responsible.

2.9.1 Strength Loss

Recently, a meta-analysis has investigated the decrease in strength following the cessation of training (Bosquet *et al.*, 2013). Similar to training adaptations, the structure of the training programme (intensity and duration) appears to influence the temporal characteristics of detraining (Bosquet *et al.*, 2013). For example, a lower rate of strength loss has been found from higher intensity resistance training when compared to lower intensity resistance training (Fatouros *et al.*, 2005). Results from the meta-analysis showed that a decrease in strength is evident by the third week following cessation of resistance training (Bosquet *et al.*, 2013). Whilst it is clear that once the training stimulus is withdrawn strength will decrease, exactly how long strength is maintained is difficult to determine. Studies have reported an increased strength above baseline from 4 weeks to 12 months following cessation of resistance training (Hakkinen *et al.*, 1985; Weir *et al.*, 1995; Taaffe and Marcus, 1997; Hakkinen *et al.*, 2000; Lemmer *et al.*, 2000; Brochu *et al.*, 2002; Trappe *et al.*, 2002; Harris *et al.*, 2007; Carvalho *et al.*, 2009; Popadic Gacesa *et al.*, 2011; Correa *et al.*, 2013). In addition to the intensity and volume of the resistance-training programme, the population under investigation has a significant influence on the rate of strength loss. Elderly and recreational individuals have shown a greater decrement in strength when compared to younger or competitively trained athletes (Bosquet *et al.*, 2013).

2.9.2 Strength Loss from Detraining after Shortening and Lengthening Resistance Training

It appears that shortening and lengthening muscle resistance training also influences the loss of strength following the cessation of resistance training. Hortobagyi *et al.* (1993) investigated the effects of 14 days inactivity on various strength related measures in previously trained power athletes. A reduction in lengthening force generating capacity was seen in all 12 athletes but not during shortening contractions.

Similar results have been seen in other work with previously trained individuals (Kraemer *et al.*, 2002). Conversely, resistance training of previously untrained males, which is then followed by cessation of resistance training, has shown lengthening contractions to be less susceptible to detraining (Andersen *et al.*, 2005). Andersen *et al*. (2005) demonstrated that following a three month resistance training programme and a three month detraining period, shortening maximal force decreased to pre-training levels; however, fast and slow lengthening contractions were maintained during the three months of inactivity. Furthermore, when lengthening contractions were coupled with shortening contractions, there was a greater preservation of shortening and lengthening strength when compared to shortening contractions alone (Colliander and Tesch, 1992).

Little information exists on the effect of lengthening only resistance training and subsequent detraining. As lengthening contractions are associated with a large amount of muscle damage and acute reductions in strength (Howatson *et al.*, 2005; Howatson and van Someren, 2008; Cockburn *et al.*, 2010), it is logical to suggest that the muscle damage from lengthening resistance training may influence the temporal characteristics of detraining. Krentz and Farthing (2010) used a 20 day lengthening resistance training protocol during which participants were trained every second day. The resistance-training protocol was then followed by a five-day detraining period. During the training period and five days detraining, there was a significant suppression of peak force. The authors attributed the reduction in strength to swelling and oedema not dissipating during the resistance training programme or detraining. If a greater recovery time is needed from lengthening resistance training when compared to shortening or isometric contractions, then the changes in peak force during periods of inactivity may also be different. Conversely, following 8 weeks of lengthening only resistance training and 8 weeks of detraining, there was an increase peak force and a maintenance of strength through the detraining (Housh *et al.*, 1996). Housh *et al*.

(1996) used an increased recovery time between each lengthening training session, which may explain the increase MVC found at the end of the training period and maintenance through detraining. However, further research investigating the effect of lengthening training and subsequent detraining is needed for more support or refute these conclusions.

No study has compared changes in force generating capacity of the muscle following shortening and lengthening resistance training and then subsequent detraining. Understanding how shortening and lengthening muscle contractions respond during periods of inactivity will effectively help periodise athletic resistance training programmes and periods of inactivity in clinical populations.

2.9.3 Neurological Modifications and Detraining

Bosquet *et al*. (2013) speculated that the sequence of resistance training adaptations were similar to detraining. More specifically, early decreases in strength are neurological or central and later decreases are due to morphological or periphery modifications. However, little consistency exists as to the neurological mechanisms responsible for the loss in strength. Numerous studies have demonstrated a reduction in EMG following the cessation of resistance training (Hakkinen and Komi, 1983; Narici *et al.*, 1989; Hakkinen *et al.*, 2000; Andersen *et al.*, 2005; Gondin *et al.*, 2006b). Following 12 weeks of resistance training, Hakkinen and Komi (1983) showed a decrease in force that was accompanied with a reduction in surface EMG. More recently, the same group showed an acute reduction in EMG following the cessation of resistance training (Hakkinen *et al.*, 2000); although EMG remained significantly higher compared to baseline values. Both studies suggest that the initial reduction in strength was due to reduced muscle activation. Further reports support this by suggesting the

time course of neurological detraining are similar to those that occur during training (Narici *et al.*, 1989).

Anderson *et al.* (2005) used a progressive three month dynamic resistance training programme to investigate adaptation to shortening and lengthening muscle contractions followed by a subsequent three month detraining period. Following three months of detraining, lengthening neural activation showed a full preservation at lower speeds, and a trend towards preservation at quicker lengthening speeds. However, activity during shortening muscle contractions showed no significant differences compared to baseline levels. Even though the study uses dynamic resistance training that consisted of shortening and lengthening muscle contractions, it provides evidence that the neurological adaptations to resistance training are preserved to a greater extent in lengthening muscle contractions. Further research should focus on comparing the neurological response to shortening and lengthening detraining following periods of task-specfic training. The use of EMG provides a global measure of neurological adaptations, however, using techniques such as TMS and PNS may provide a greater insight into the exact neurological mechanisms responsible for the decrease in strength following the cessation of training.

No study has used TMS and PNS related measures to investigate the neurological mechanisms responsible for the loss in strength following the cessation of resistance training. However, numerous studies have focused on corticospinal changes during extended periods of inactivity. Similar to detraining following the cessation of resistance training, periods of inactivity have shown a reduction in strength (Baldwin *et al.*, 1996). The exact modifications at a corticospinal and spinal level remain speculative. A large decrease in spinal excitability has been reported after 20 days of bed rest (Yamanaka *et al.*, 1999). Conversely, numerous studies have reported an increase in spinal

excitability (Anderson *et al.*, 1999; Clark *et al.*, 2006). Differences may be linked to the two different methods for unloading the limb. Changes in corticospinal excitability through detraining also appear to follow a similar trend as through resistance training with little consistency in the literature (Sato *et al.*, 2000; Miyazaki *et al.*, 2002). As the modifications at the corticospinal and spinal level appear to be linked to the mode of inactivity, it is difficult to conclude with any certainty the exact changes that occur following the cessation of resistance training.

2.10 General Summary

TMS and PNS have been increasingly used to investigate neurological adaptations. However, the reliability of these measures has been predominantly assessed at rest or during isometric contraction. Whilst these conditions arguably allow a very repeatable measure, the validity they have to dynamic muscle contractions that occur in everyday tasks is debatable. As demonstrated in this review, lengthening contractions have unique neurological characteristics; therefore, it seems logical that TMS and PNS responses should be assessed during dynamic muscle contractions. Consequently, the repeatability of TMS and PNS related measures during shortening and lengthening contractions needs to initially be established in this thesis.

Despite the increasing use of TMS to investigate corticospinal adaptations from resistance training, the numerous different training protocols and methods have led to little consistency amongst findings and therefore the exact changes in measures such as corticospinal excitability and inhibition remain unclear. Furthermore, little research has used TMS and PNS in the same protocol to investigate adaptations at multiple levels of the nervous system for acute and chronic resistance training adaptations. In resistance-trained individuals, little is known on how the neurological system is modified to increase the force generating capacity of the muscle. Acute and chronic

adaptations to resistance training has focused on neurological adaptations during isometric conditions, however, unique neurological adaptations have only been shown in lengthening contractions of resistance trained athletes. This further emphasises the notion that neurological resistance-training adaptations should be assessed during dynamic contractions.

Given the importance of lengthening contractions in rehabilitation and resistance training programmes, it is surprising that no research has used these techniques to isolate the mechanisms of lengthening compared to shortening acute resistance training adaptations. Given that lengthening contractions have a greater potential for neurological modifications and strength gains, a better understanding of acute neurological adaptations to lengthening and shortening contractions will ensure clinicians can maximise rehabilitation programmes. Finally, of the limited data investigating changes in the nervous system following the cessation of training, only EMG data exists. Investigating the detraining process may increase our understating of inactivity in aging and maximise athletes training programmes. Following the review of literature, this thesis will answer the following important issues that have arisen.

The overall aim of the thesis is to examine corticospinal and spinal responses following shortening and lengthening resistance training Specifically, in a series of three experimental chapters the aims are:

1. To examine the repeatability of TMS and PNS during lengthening and shortening muscle contractions.
2. To examine the TMS and PNS responses in chronic resistance trained and untrained individuals during shortening and lengthening muscle contractions.
3. To examine the acute (4 weeks) TMS and PNS responses from shortening and lengthening resistance training and subsequent detraining.

Chapter 3: Methods

Part I

3.1 Introduction

This chapter outlines the methods used throughout this thesis. Specific methods used in individual experimental chapters are discussed within the corresponding chapters.

3.2 Testing Procedures

3.2.1 Ethical Approval

Prior to the start of each investigation, ethical approval was gained from Northumbria University Ethics Committee in accordance with the Declaration of Helsinki.

3.2.2 Participants

An outline of the total number of participants and allocation to each individual experiment can be seen in Appendix A. All participants were screened for neurological disorders, pacemakers and intracranial plates, in accordance with recommendations for the safe use of TMS (Rossi *et al.*, 2009; Rossi *et al.*, 2011) (Appendix B). Following screening, participants provided written, informed consent (Appendix C). The dominant leg was selected for testing and was determined using a previous method (Hebbal and Mysorekar, 2006), which included asking participants to stamp the ground, kick a soccer ball and push an object with their foot. Participants were asked to arrive in the laboratory in a well-hydrated state having refrained from the participation of strenuous exercise in the previous 48 h. Additionally, instructions were given to participants to refrain from caffeine on the assessment days, avoid alcohol within 24 h and refrain from eating within 1 h prior to testing. All testing was conducted in the biomechanics laboratory of Northumbria University.

3.2.3 Anthropometry

Before any experimental procedure, participants height, mass and age were recorded. Height was recorded to the nearest cm using a calibrated stadiometer (Holtain, Crymych, Wales), in accordance with the International Society for Advancement of Kinanthropometry guidelines. On calibrated scales (Marsden MPCS-250, Oxfordshire, UK), mass was recorded to the nearest 0.1 kg and age was recorded to the nearest year. In line with previous work using TMS measures (Kamen, 2004) and to avoid any change in muscle function (Drust *et al.*, 2005) through diurnal variation, participants were tested at the same time of day in each experiment.

3.2.4 Experimental Set-up

The tibialis anterior (TA) in humans has a uniquely high corticospinal drive during the gait cycle whilst walking (Capaday *et al.*, 1999) and has previously been shown to be an excellent candidate for neurological assessment using TMS (Cacchio *et al.*, 2009; Cacchio *et al.*, 2011). Additionally, the accessibility of the common peroneal nerve through electrical stimulation (Palmieri *et al.*, 2002) ensures the TA can be assessed at multiple levels of the CNS. Figure 3.1 shows an example of the experimental set-up used in this thesis.

Participants were seated in an isokinetic dynamometer in a position to measure the dorsiflexors, as recommended by the manufacturer's guidelines (Cybex Norm, Cybex International, NY) with the hip, knee and ankle of the dominant leg set at joint angles of 90, 120 and 90°, respectively. The foot of the dominant leg was firmly strapped into the ankle adapter of the dynamometer, whilst the knee was secured in a thigh stabiliser to prevent any extraneous movement of the upper leg. Participants performed dorsiflexion by resisting or assisting (dependent upon contraction type) as the dynamometer moved

through 30° of dorsi- and plantar-flexion. The speed was set at 15°/s and torque feedback was displayed on the monitor of the dynamometer approximately 1 m from the participant.

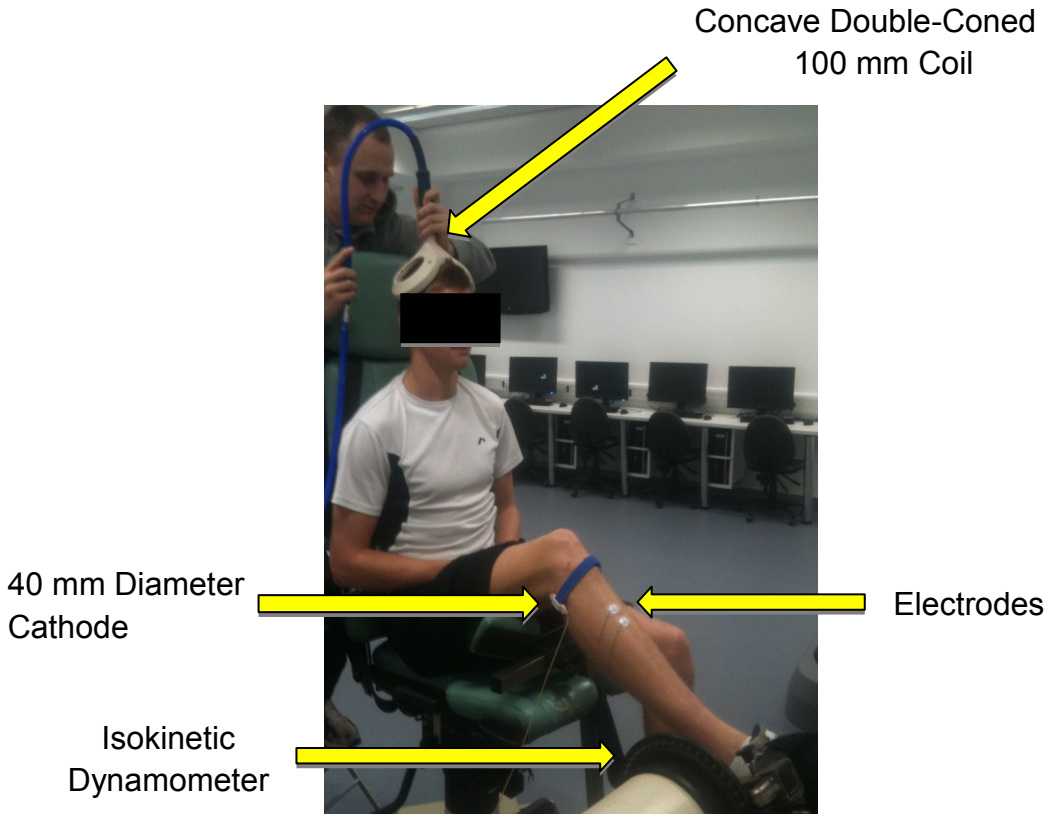

Figure 3.1 Example of experimental set-up.

3.2.5 Torque Assessment

From a starting position of 75° for lengthening and 105° for shortening contractions, torque was recorded as the ankle passed anatomical zero (90°) at a set speed of 15°/s (2s contraction). Torque was recorded off line (Signal v3.0, Cambridge Electronics, Cambridge, UK), directly from isokinetic dynamometer as a raw analogue signal (mV) and converted to force (N·m) via regression analysis (Appendix D). To ensure torque and EMG were recorded at the correct angle, a trigger was set to automatically sweep as the ankle passed 90°. Clear instructions were given to participants in order to reach the target force as quickly as possible and maintain the required force throughout the duration of the contraction.

3.2.6 Maximal Voluntary Contraction

Participants were instructed to focus on solely activating their TA. The highest value from 3 trials was recorded as the maximal MVC for each individual muscle action. From the maximal values, 80, 50, 25 and 15% of shortening and lengthening MVC were calculated. Participants also performed an isometric MVC with the ankle set at 90º. An isometric contraction of 10-15% MVC was used to stabilise the H-reflex to maximal M-wave (M_{MAX}) curve (H-M).

3.2.7 TMS Procedure

EMG was recorded 50 ms prior and 500 ms post the magnetic stimulation. MEP's were elicited via stimulation on the contralateral hemisphere of the dominant leg using a magnetic stimulator (Magstim 200^2, Magstim Company Ltd, Whitland, UK), with a concave double-coned 110 mm coil (maximal output of ~1.4 T). The 'hotspot' or optimal site for activation of the TA, has previously been reported (Devanne *et al.*, 1997) to be approximately 0.5-1 cm posterior and along the anteroposterior plane of the vertex, thus searching began here. The coil was positioned to induce a postero-anterior current in the underlying motor cortex. Once optimal coil placement was established, the position was marked directly on the scalp with a permanent marker to ensure consistent placement on subsequent trials. Resting motor threshold (rMT) was determined as the lowest stimulator output needed to evoke a peak-to-peak MEP $\geq$50 μV in 5 out of 10 consecutive pulses (Rossini *et al.*, 1994). The rMT was recorded as a percentage of maximal stimulator output and all subsequent MEPs in the respective chapters recorded at rest and during contractions, were delivered at a stimulator output equivalent to 120% rMT. The MEP amplitudes were normalised to peak-to-peak M_{MAX}. Electromyography was recorded 50 ms prior to magnetic stimulation and 500 ms post. The MEPs were reported relative to the highest M-wave (M_{MAX}) during the H-M recruitment curve (see peripheral electrical stimulation procedure). Little is known regarding the appropriate rest time between TMS pulses to ensure the MEP is not

facilitated in following contraction. Therefore, part II of this chapter will investigate the restoration time of MEP's following high and low intensity, shortening and lengthening muscle contractions. Previous research has shown mathematical modelling of the silent period to be extremely reproducible (Damron *et al.*, 2008). Therefore, the cortical silent period was measured as the distance from the stimulation artefact to a return of 1 SD of pre-stimulus EMG activity during 80% MVC of the respective contractions.

3.2.8 Percutaneous Nerve Stimulation Procedure

Electrical stimulation was administrated below the head of the fibula, over the peroneal nerve using a 40 mm diameter cathode/anode arrangement (pulse 1 ms; Digitimer DS7AH, Welwyn Garden City, Hertfordshire, UK). To ensure a stable H-reflex, each participant was instructed to hold an isometric dorsiflexion contraction of 10-15% MVC. Once the optimal site of stimulation was established, the site was marked with semi-permanent ink and the stimulator strapped to the participant's leg. The H-M recruitment curve consisted of a minimum of 64 pulses below the first appearance of H-reflex and $M_{MAX.}$ The max H-reflex was defined as the average of the three highest responses (Dragert and Zehr, 2011).

Following the H-M recruitment curve participants performed 12 shortening and 12 lengthening contractions at 25% MVC. Previous work has shown a minimum period of 25 s should be left between contractions to ensure the H-reflex has returned to pre resting states (Howatson *et al.*, 2011). Consequently, each contraction in this thesis was separated by 60 s. A low contraction intensity was used to ensure the H-reflex in the TA was easily identifiable within the background EMG. Similar to others (Crone and Nielsen, 1989; Field-Fote *et al.*, 2006), stimulator output was manipulated to elicit a H-reflex with an M-wave amplitude of 15 - 25% of M_{MAX}. Contractions that did not meet these criteria were rejected from subsequent analyses. As the amplitude of M_{MAX} is affected by intensity of contraction (Lee and Carroll, 2005), the first two of the 12

lengthening and shortening muscle contractions were used to determine individual intensity specific M_{MAX} amplitudes. It took the examiner between 2-4 contractions to achieve the appropriate stimulator intensity. Participants were passively moved in to position 10 s before performing a submaximal contraction, targeted at 10-15% MVC to prevent any thixotropic effect (Proske *et al.*, 1993). Finally, participants' V-wave was examined with four maximal shortening and lengthening contractions with a supramaximal stimulus 150% of M_{MAX} (Aagaard *et al.*, 2002). V-wave was normalised to resting M_{MAX} from the H-M recruitment curve.

3.2.9 Electromyography

Surface EMG was recorded over the TA using pairs of electrodes (22 mm diameter, model; Kendall, Tyco Healthcare Group, Mansfield, MA, USA) spaced 2 cm apart. For the TA, electrodes were placed at one-third distance of the line between the tip of the fibula and the tip of the medial malleolus (Hermens *et al.*, 2000). Electrodes for the lateral gastrocnemius were place at one-third distance of the line between the head of the fibula and the calcaneus. The reference electrode was placed over the medial malleolus. All sites were shaved, abraded with preparation gel and then wiped clean with an alcohol swab. EMG was amplified (×1000), band pass filtered 10-1,000 Hz (D360, Digitimer, Hertfordshire, UK) and sampled at 5,000 Hz (CED Power 1401, Cambridge Electronics Design, Cambridge, UK).

Part II: Method Development

3.3 Introduction

Peak-to-peak MEP amplitude has commonly been shown to increase following voluntary muscle contractions of between 2 and 60 seconds (Samii *et al.*, 1997; Nørgaard *et al.*, 2000; Balbi *et al.*, 2002). Previous research has predominantly focused on such short duration isometric (ISO) contractions with little information regarding dynamic contractions. The balance between cortical and spinal facilitation and inhibition is different between lengthening and shortening contractions (Duclay *et al.*, 2011) , hence the time course of MEP recovery to baseline may also differ. Therefore, the aim of this section was to determine the recovery time of resting MEP amplitude following lengthening and shortening muscle contractions at higher and lower contraction intensities. These results will inform the methods used in the forthcoming experimental chapters.

3.4 Materials and Methods

Following institutional ethical approval (RE07-01-12538), eight volunteers (7 men and 1 woman, mean ± SEM mean age 26 ± 1 years, 176 ± 3 cm, 76.0 ± 3.1 kg) completed a health-screening questionnaire and provided written informed consent. Shortening and lengthening muscle contractions of the dominant TA were performed at 25 and 80% of the contraction specific MVC on an isokinetic dynamometer. The MEPs were evoked by cortical stimulation of M1 as previously described in section 3.2.7; using a concave double-cone coil (110 mm) powered by a magnetic stimulator. Once the 'hotspot' was detected, rMT was established. All subsequent stimulations at rest and during contractions were delivered at a stimulator output equivalent to 120% rMT.

EMG Electrodes were placed 2 cm apart on the belly of the TA. EMG signals were amplified (×1000), band-pass filtered 10 – 1,000 Hz (D360, Digitimer, Hertfordshire,

UK) and sampled at 5,000 Hz (CED Power 1401, Cambridge Electronics Design, Cambridge, UK). The isokinetic speed was 15°/s and the starting position was 75º for lengthening and 105º for shortening contractions. The stimulator was discharged as the ankle passed anatomical zero and the subsequent MEPs were recorded. Target torque and actual 'real-time' torque were displayed on the Cybex computer monitor in view of the participant. Volunteers performed lengthening and shortening contractions at 25 and 80% of the task specific maximal voluntary contraction (MVC) in a randomised order (SHO25: SHO80: LEN25: LEN80). Immediately following the contraction, the ankle was passively returned to 90º and resting MEPs were evoked for 60 s at 10 s intervals. The mean MEP response from five stimuli during each task was used for data analysis. A repeated measures ANOVA was used to detect changes between MEP characteristics.

3.5 Results

rMT was 46 ± 2% of the stimulator output. Participants produced significantly greater torque ($t_{(7)} = 6.0$; $P = 0.001$; 95% CI 9.2 – 21.2 N·m) during a lengthening (47.7 ± 2.4 N·m) when compared to shortening MVC (32.5 ± 1.5 N·m). Figure 3.2 shows the restoration time of MEPs following high and low intensity shortening and lengthening muscle contractions, whilst Figure 3.3 is a representative trace.

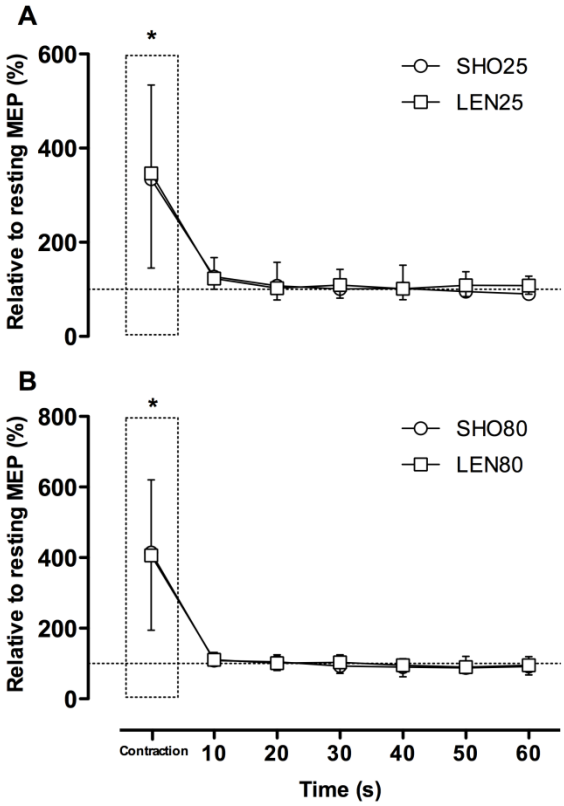

Figure 3.2 Restoration time of MEPs following 25% (**A**) and 80% MVC (**B**) shortening and lengthening muscle contractions.

The MEPs were significantly ($P \leq 0.002$) facilitated during shortening and lengthening contractions compared to rest (SHO25: 95% CI 0.64 – 1.71 mV; SHO80: 95% CI 1.22 – 2.18 mV; LEN25; 95% CI 0.54 – 1.65 mV; LEN80: 95% CI 1.05 – 2.05 mV). There were no significant differences between shortening and lengthening MEPs at 25% MVC or 80% MVC ($P > 0.05$). However, the torque/MEP ratio revealed significantly lower MEPs for lengthening contractions at 25% MVC ($t_{(7)}$ = P= 0.028; 95% CI 0.01 – 0.16%) and 80% MVC ($t_{(7)}$ = P= 0.003; 95% CI 0.03 – 0.10%) when compared to shortening contractions. There were no significant differences in MEP amplitude 10 s post-contraction during shortening or lengthening contractions at 25 and 80% MVC in

relation to the relative resting values (P > 0.05). Compared to MEP at rest, no significant differences were seen in MEP amplitude 10 s post contraction during shortening and lengthening contractions at 25 and 80% MVC (P > 0.05).

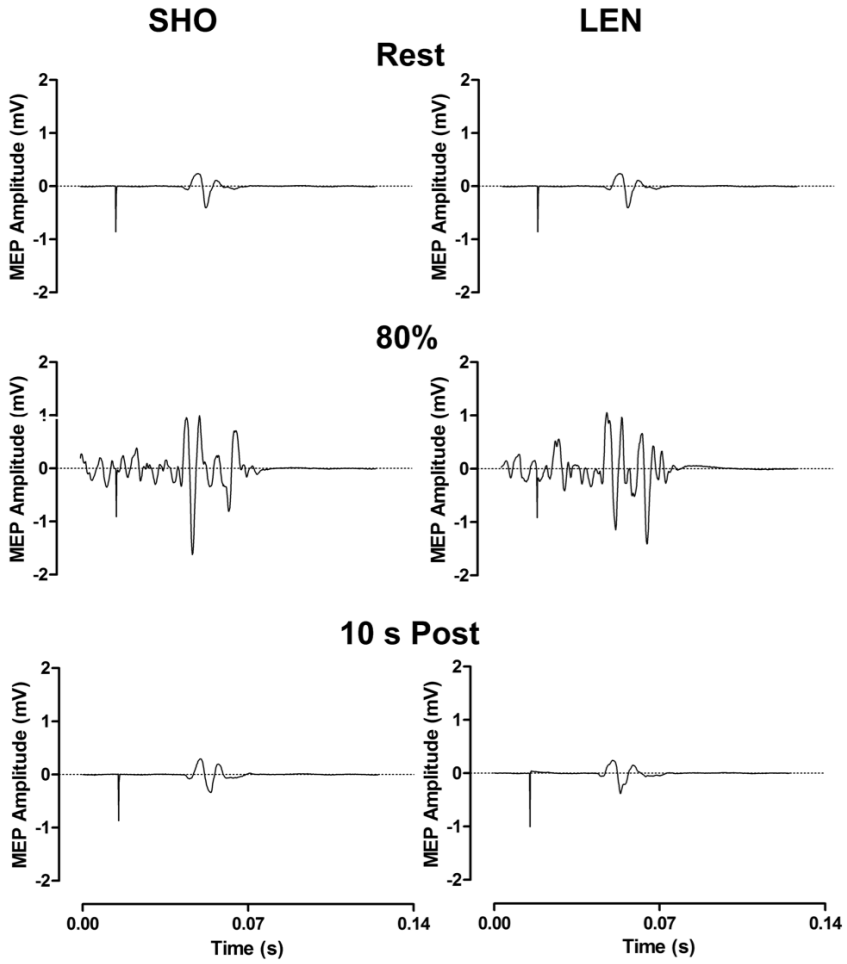

Figure 3.3 Representative trace of MEPs during rest, 80% shortening and lengthening MVC and 10 s post.

3.6 Discussion

The increase in MEPs after a non-fatiguing muscle contraction is due to an excess release of acetylcholine at the motor end plate (Brasil-Neto *et al.*, 1993), the most likely cause for changes at the muscle is due to increase facilitation within the motor cortex (Samii *et al.*, 1996; Nørgaard *et al.*, 2000). Although the results from this study did not

show evidence of a task dependent MEP, previous work has shown a smaller MEP during lengthening than shortening contractions (Sekiguchi *et al.*, 2007; Duclay *et al.*, 2011). Therefore the possibility exists that the after-effects of these muscle contractions are also task and perhaps intensity specific. Whilst supporting these task specific differences, the findings here are the first to demonstrate that the recovery of MEPs from shortening contractions echo that of lengthening, and show no evidence of task specific modulations from the respective contractions. Therefore, the augmented neurotransmitter release appears to be short-lasting (< 10 s) and not contraction specific. With no task specific changes reported in the recovery of resting H-reflex in the flexor carpi radialis (Howatson *et al.*, 2011), it appears contraction type might have little influence on the recovery of cortical or spinal responses.

Previous research reported MEPs were still facilitated 1 s but not 15 s after isometric contraction of the bicep brachii and thenar muscles in contraction intensities 25 -100% MVC (Nørgaard *et al.*, 2000; Balbi *et al.*, 2002). The authors reported that the length of contraction has a greater influence on the recovery of the MEP than the contraction intensity. The data in this chapter shows no change in recovery of MEPs between 25% and 80% MVC; hence it seems contraction intensity (at least in this intensity range) has little effect on the recovery of MEPs.

The lack of MEP facilitation 10 s post-contraction seems surprising given that cervicomedullary stimulation of the TA has caused longer lasting changes in MEP amplitude several minutes after the contraction compared to upper limb muscles (Giesebrecht *et al.*, 2010). However, the shortest contraction duration in that study (Giesebrecht *et al.*, 2010) was 10 s, compared to a 2 s contraction used here. Therefore, future research might focus on slower/longer duration shortening and lengthening contractions. In summary, these data suggest that 2 s shortening and

lengthening contractions produced 3-4 fold facilitation of the MEP, but MEP amplitude returns to pre-contraction level within 10 s.

3.7 Perspective

The aim of this method development section was to establish the appropriate time period between TMS superimposed contractions, to ensure there was no facilitation of the MEP in the subsequent contraction. Firstly, there was no significant difference between the recovery time of MEPs during shortening and lengthening at high and low intensity contractions. Therefore, the same rest period between contractions can be employed regardless of the action type and intensity. Based on the above results, a rest period of greater than 10 s between contractions superimposed with TMS pulses will be used in subsequent chapters. This chapter has also provided clinicians investigating conditions such as foot drop information on the minimal time between TMS pulses during dynamic conditions. With only 10 s between pulses, clinicians and researchers can record multiple pulses in a relatively short period of time, reducing the time required of both parties.

Chapter 4:

Repeatability of Corticospinal and Spinal Measures during Lengthening and Shortening Contractions in the Human Tibialis Anterior Muscle

4.1 Introduction

Since originally proposed by Barker *et al*. (1985) as a non-invasive and pain free method to examine transient functional lesions of the brain (Hallett, 2000), transcranial magnetic stimulation (TMS) is a widely used tool to examine motor cortical physiology (Hallett, 2000; Rothwell, 2007). Relatively few studies (Herwig *et al.*, 2001; Kamen, 2004; Malcolm *et al.*, 2006; Cacchio *et al.*, 2011) have examined the stability and consistency of TMS measures that provide information on excitability and plasticity of the human nervous system. This is surprising because there are at least two main sources of variation that can affect the stability of TMS measures. One is the constant oscillation in the elements of the human central nervous system (CNS), including the neurons forming the corticospinal tract (Kiers *et al.*, 1993; Ellaway *et al.*, 1998; Darling *et al.*, 2006) that contribute to the variable nature of TMS measures. A second source of variation is methodological, in particular, the level of muscle torque and the changing muscle mechanics (Carroll *et al.*, 2001; Kamen, 2004; Darling *et al.*, 2006), subject population and the muscle under investigation (Kamen, 2004; Malcolm *et al.*, 2006). To emphasise the need for determining the consistency and stability of TMS measures, studies have shown that a few forceful muscle contractions or repetitive contractions can readily modulate the excitability of the intact human primary motor cortex (M1) (Classen *et al.*, 1998; Kamen, 2004; Selvanayagam *et al.*, 2011). In addition, many of these TMS protocols were administered over several days, but virtually none of these studies report what, if any, effects are due to repeat TMS measurements *per se*. Therefore, it is important to determine the magnitude of day-to-day variation that is due to the administration of the TMS measurements.

The use of TMS in combination with other neurophysiological measures are needed to assess if changes in M1 are mediated at a spinal level (Carroll *et al.*, 2011). One such measurement that can complement TMS is provided by the peripheral nerve stimulation (PNS) producing the Hoffman reflex (H-reflex) (Hoffmann, 1910; Palmieri *et*

al., 2004). As discussed in section 2.3.2, the H-reflex represents motoneuron excitability and presynaptic inhibition of the motoneuron reflex arc (Aagaard *et al.*, 2002; Zehr, 2002; Knikou, 2008). The reliability of the H-reflex is well established at rest in the soleus (Hwang, 2002; Palmieri *et al.*, 2002; Robertson and Koceja, 2004; Mynark, 2005), but less is known about the day-to-day variation in other muscles such as the TA (Palmieri *et al.*, 2002), or whilst the muscle changes in length (Simonsen and Dyhre-Poulsen, 2011). Compared to shortening and isometric contractions, lengthening muscles contractions appear to possess unique neurological characteristics in several elements of the CNS between M1 and motor units (Enoka, 1996; Duchateau and Enoka, 2008) and it is unclear if these characteristics would affect between-day stability of TMS and PNS measures. Furthermore, TMS or H-reflex measures alone provide limited information; coupling these techniques in the same exercise paradigm gives further detail of changes in excitability at multiple levels of the CNS. To date, no study has established the repeatability of these methods in a single experiment.

Despite the increasing amount of experimental studies using TMS and PNS (Sekiguchi *et al.*, 2003; Sekiguchi *et al.*, 2007; Duclay *et al.*, 2009) during dynamic contractions, only a few studies have investigated the repeatability of TMS or PNS in the TA (Palmieri *et al.*, 2002; Cacchio *et al.*, 2009; Cacchio *et al.*, 2011; Duclay *et al.*, 2011). Surprisingly, there is even less information on the repeatability of these measures during dynamic muscle contractions (van Hedel *et al.*, 2007; Simonsen and Dyhre-Poulsen, 2011). To date, no study has investigated the day-to-day repeatability of TMS and PNS measures in a single trial during dynamic contractions in the TA. A repeatable method to assess cortical and spinal responses from day-to-day may help further understand neurological conditions in the TA. However, as the overall aim of this thesis is to assess corticospinal and spinal adaptations from resistance training, the main objective of this chapter is ensure TMS and PNS are repeatable. An increasing number of studies are using TMS and PNS to detect and quantify neurological adaptations; it is

vital that stimulation techniques are reproducible. Furthermore, with numerous variables influencing the reproducibility of the stimulation responses, establishing the error of the measurement will allow insight into the magnitude of adaptations in chapters five and six. Thus, the aim of the present chapter was to assess the day-to-day repeatability of commonly used measures of neuromuscular function and adaptation using both TMS and PNS during lengthening and shortening muscle contractions.

4.2 Materials and Methods

4.2.1 Participants

Prior to the start of the investigation, ethical approval was gained from Northumbria University Ethics Committee (RE07-01-12538) in accordance with the Declaration of Helsinki. Twenty healthy males volunteered were recruited to take part in the study (mean ± SD age, 24 ± 3 yrs; stature, 177 ± 7 cm, mass, 82.1 ± 2.9 kg). As discussed in section 3.2.2, participants were screened for neurological disorders. Of the 20 participants, 18 were right and 2 were left leg dominant.

4.2.2 Experiment Design

Participants reported to the laboratory on 3 consecutive days for up to 120 min at the same time of day to avoid diurnal variation. Contraction type (lengthening and shortening), intensity (80, 50, 25 and 15% MVC) and the order of TMS and PNS were randomised for each participant. The order was kept consistent for each participant on days 1, 2 and 3. The participants were asked to arrive in a rested state as described in section 3.2.2.

4.2.3 Experimental Set-up

For experimental set up, please see 'General Methods' section 3.2.4.

4.2.4 Maximal Voluntary Contraction

At the beginning of the initial testing session, shortening, lengthening and isometric MVC of the TA were recorded. For full procedure of MVC, see 'General Methods' 3.2.6.

4.2.5 Electromyography

For electromyography, please see 'General Methods' section 3.2.4.

4.2.6 Transcranial Magnetic Stimulation Protocol

Exact details of the TMS protocol specific to this chapter are described below; for detailed description of the method used to established the 'hotspot', resting motor threshold (rMT) and resting MEP, please see Section 3.2.7. After establishing rMT, MEP's were elicited at 120% rMT. In a randomised but counterbalanced order, participants performed shortening or lengthening contractions at 80, 50, 25 and 15% MVC. All contractions were separated by at least 25 s based on the findings from Chapter 3, Part II. The corticospinal silent period was recorded during 80% MVC. Participants performed eight contractions at each intensity; the average was recorded and used for data analysis. In most cases, it took 2-3 attempts for participants to become competent at achieving the required force. Clear instructions were given to reach the target force as quickly as possible and maintain the required force throughout the duration of the contraction.

4.2.7 Peripheral Electrical Stimulation Procedure

For detailed description of PNS measures (H-M recruitment curve, H-reflex during shortening and lengthening muscle contractions and V-wave), see section 3.2.8. Participants initially performed the H-M recruitment curve, followed by lengthening and shortening muscle contractions at 25% MVC of the respective contractions. Finally, V-wave was evoked during maximal contractions.

4.2.8 Data Analysis

EMG was recorded 50 ms prior and 500 ms post to magnetic stimulation. The MEPs, cortical silent period and torque were all analysed post trials (Signal 3.0, Cambridge Electronics, Cambridge, UK). The MEP amplitudes and V-waves were normalised to peak-to-peak M_{MAX}. H-reflex during shortening and lengthening 25% MVC was normalised to relative M_{MAX}.

4.2.9 Statistics

Data is presented as mean ± SD. To detect significant differences in all parameters (apart from torque) between days, a one way repeated measures ANOVA was conducted. Two-way repeated measures ANOVA on day (1, 2 and 3) and contraction intensity (80, 50, 25 and 15%) was used to examine differences for lengthening and shortening MEPs. A three-way repeated measures ANOVA for day, contraction type (shortening and lengthening) and contraction intensity was used to test for within group differences in torque. If significant interactions were revealed, pairwise LSD *post-hoc* comparisons were made. Between-day repeatability for each of the variables was assessed by intraclass correlation coefficient (ICC) analyses from days 1-2, 2-3 and across the three days. Additionally, 95% confidence intervals (CI) were determined to assess the magnitude of change and the coefficient of variation (CV) was determined

to assess the reliability between days. Statistical analyses were performed using SPSS (v17.0, Chicago, Illinois, USA).

4.3 Results

A repeated measures ANOVA showed no significant differences ($P > 0.05$) in relative torque over the 3-day period (Table 4.1). Therefore, TMS and PNS variables were evoked under the similar contraction intensities between contraction types across the three days. Despite rMT remaining stable, resting MEP was significantly ($F_{(1,19)} = 4.1$; $P = 0.025$) different between days (Figure 4.1). Post-hoc analysis revealed a significant difference in MEP/M_{MAX} between days 1-2 ($P = 0.016$; 95% CI 0.00 - 0.04) and 1-3 ($P = 0.046$; 95% CI 0.00 - 0.03) with no difference between days 2-3. A representative trace of the MEPs evoked at different intensities during shortening and lengthening is presented in Figure 4.2. Across the three days, there was no change in shortening ($P = 0.11$) or lengthening ($P = 0.14$) MEPs (Figure 4.3). There was no significant difference in the cortical silent period across the three days (shortening; $P = 0.79$; lengthening; $P = 0.13$); a representative trace of the cortical silent period across the 3 days for both contraction types is presented in Figure 4.4. No significant differences were reported between days for any PNS variables (Table 4.2).

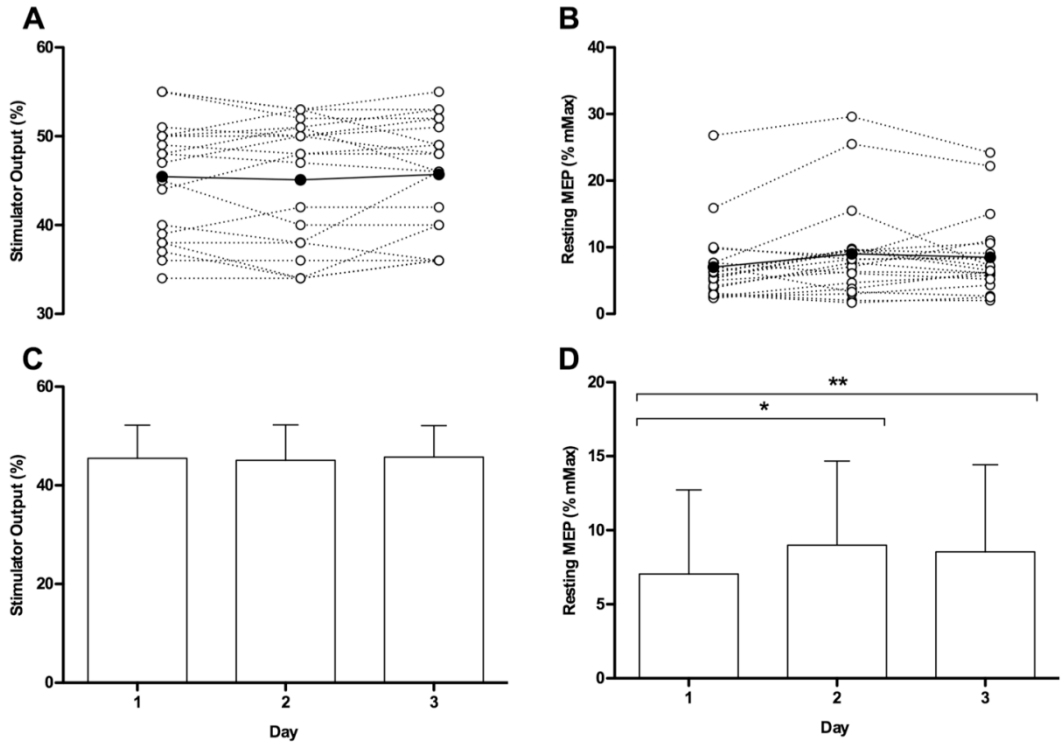

Figure 4.1. Individual resting motor threshold as a percentage of stimulator output. Clear dots represent individual participants whilst filled dots represent mean data (**A**). Individual and mean resting motor evoked potentials (MEPs) (**B**). Mean resting motor threshold (**C**) and mean resting MEPs as a percentage of M_{MAX} (**D**) on day 1, 2, and 3. *(P = 0.016) and **(P = 0.046) denotes significant difference.

Excluding those evoked at 80% shortening MVC, MEPs showed good reliability (ICCs = 0.79 – 0.92) across the three days (Table 4.3 Resting MEPs had the highest overall error (CV = 28.9%) compared to both contraction types and across intensities. Cortical silent period and rMT demonstrated the lowest variability (CV < 7.5%) compared to any other cortical response. Reliability varied from moderate to high (ICC = 0.54 – 0.84) for PNS related variables, but showed a predominantly higher CV (11.7 – 29.3%) than TMS variables. Unlike TMS, there was no apparent familiarisation effect with PNS.

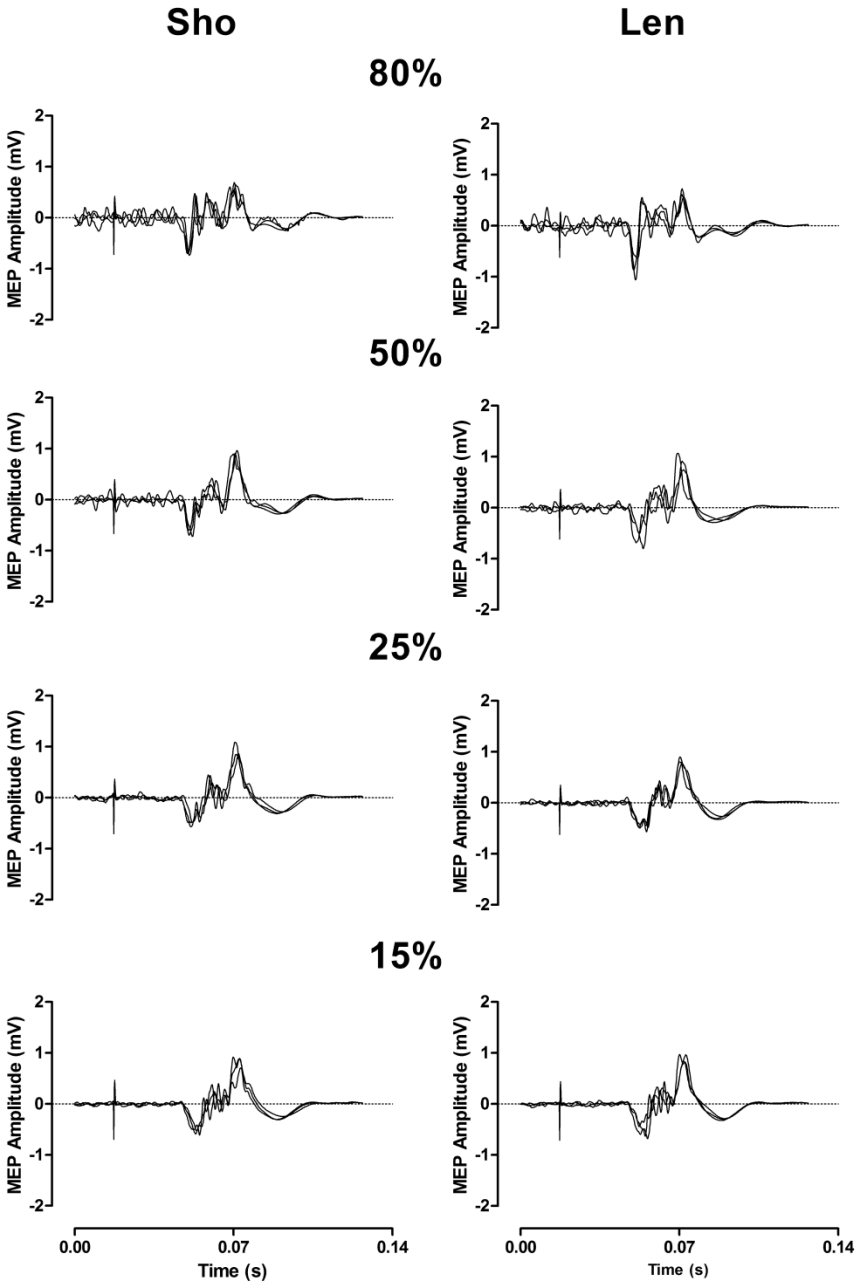

Figure 4.2 Representative traces of motor evoked potentials overlaid across the three days at 15, 25, 50 and 80% of relative maximal voluntary contractions.

Table 4.1 Force (% MVC) of the TA during different shortening and lengthening contraction intensities during TMS and PNS (mean ± SD).

TMS								PNS	
HO	EN	HO	EN	HO	EN	HO	LEN	HO	LEN
Target Torque (%)									
15		25		50		80		25	
± 6.22	± 3.95	± 4.09	± 7.54	± 6.71	± 7.95	± 12.0	1 ± 5.85	± 7.23	1 ± 6.78
± 3.80	± 3.26	± 5.90	± 5.41	± 7.81	± 7.86	± 9.21	± 10.66	± 4.26	3 ± 7.49
± 4.72	± 2.95	± 4.04	± 5.12	± 7.26	± 8.45	± 9.57	3 ± 9.08	± 4.42	) ± 3.82

TMS, Transcranial Magnetic Stimulation; PNS, Peripheral Nerve Stimulation; ISO, Isometric; SHO, Shortening; LEN, Lengthening

Table 4.2 Mean ± SD for PNS variables across three consecutive days. M_{MAX} (mV), H-reflex (% M_{MAX}), V-wave (% M_{MAX}).

	I_{MAX}	H-reflex	) H-reflex	H-reflex	V-wave	V-wave
1	± 0. 26	7 ± 3.5	.7 ± 6.0	6 ± 4.2	0 ± 2.0	.8 ± 1.2
2	± 0.36	0 ± 4.5	.7 ± 5.9	0 ± 3.9	1 ± 1.7	.5 ± 1.3
3	± 0.30	0 ± 5.0	.4 ± 6.2	3 ± 3.9	4 ± 1.8	.6 ± 1.8

PNS, Peripheral Nerve Stimulation; ISO, Isometric; SHO, Shortening; LEN, Lengthening

Table 4.3 Coefficient of variation (CV), change in mean confidence intervals (CI) and intraclass correlation coefficients (ICC) across the three days, between days 1 and 2 (D1-D2) and days 2 to 3 (D2-D3) for corticospinal variables.

	ICC			% Change in Mean (95% CI)		CV (%)		
	Overall	D1-D2	D2-D3	D1-D2	D2-D3	Overall	D1-D2	D2-D3
rMT	0.93	0.94	0.92	−0.77 (−3.7 - 1.8)	1.33 (−1.6 - 5.0)	3.2	3.2	3.3
Rest MEP	0.87	0.88	0.89	27.7 (−0.2 - 54.1)	−5.01 (−15.5 - 13.5)	28.9	30.4	15.7
SHO MEP 15%	0.83	0.86	0.82	9.15 (−2.0 - 17.8)	−3.74 (−15.0 - 7.4)	13.2	11.7	13.3
SHO MEP 25%	0.92	0.95	0.89	9.74 (4.5 - 16.1)	−2.05 (−10.0 - 3.3)	9.7	8.8	8.8
SHO MEP 50%	0.79	0.73	0.81	3.84 (−5.0 - 14.7)	0.58 (−10.4 - 8.1)	12.7	11.6	11.3
SHO MEP 80%	0.63	0.52	0.73	4.38 (−10.8 - 20.5)	5.58 (−4.3 - 18.5)	15.4	15.1	12.7
LEN MEP 15%	0.88	0.86	0.90	−2.89 (−13.1 - 6.4)	3.64 (−5.2 - 14.0)	12.1	12.4	10.1
LEN MEP 25%	0.88	0.84	0.92	−2.51 (−13.2 - 5.7)	−2.38 (−7.3 - 4.9)	11.3	11.1	7.4
LEN MEP 50%	0.84	0.83	0.85	−3.27 (−14.3 - 7.6)	3.00 (−7.3 - 14.7)	12.3	12.1	11.7
LEN MEP 80%	0.81	0.69	0.92	−1.90 (−14.7 - 8.7)	−0.22 (−5.4 - 6.9)	13.2	13.9	7.7
SHO SP	0.94	0.94	0.94	0.61 (−6.1 - 6.2)	0.96 (−2.7 - 8.9)	7.4	6.1	5.8
LEN SP	0.96	0.98	0.94	3.24 (−0.8 - 7.6)	1.66 (−2.2 - 8.0)	4.6	6.7	7.1
M_{MAX}	0.66	0.72	0.66	−0.14 (−10.3 - 8.6)	2.67 (−4.6 - 18.0)	11.7	10.9	12.3
H-reflex	0.65	0.65	0.66	2.20 (−13.5 - 14.2)	7.50 (−7.1 - 26.6)	19.1	15.7	17.7
SHO-H-reflex	0.84	0.83	0.85	0.28 (−11.6 - 15.3)	5.17 (−6.0 - 17.4)	15.5	12.2	15.4
LEN H-reflex	0.76	0.79	0.74	−6.14 (−16.7 - 11.9)	−1.80 (−22.3 - 8.8)	16.1	17.2	20.5
SHO-V-wave	0.77	0.76	0.76	−4.44 (−16.7 - 11.7)	−6.48 (−22.9 - 8.6)	22.0	17.3	16.4
LEN-V-wave	0.54	0.35	0.63	11.6 (−9.4 - 39.8)	8.22 (−30.2 - 6.4)	29.3	27.1	25.4

rMT, Resting Motor Threshold; MEP, Motor Evoked Potentials; SHO, Shortening; LEN, Lengthening; SP, Silent Period

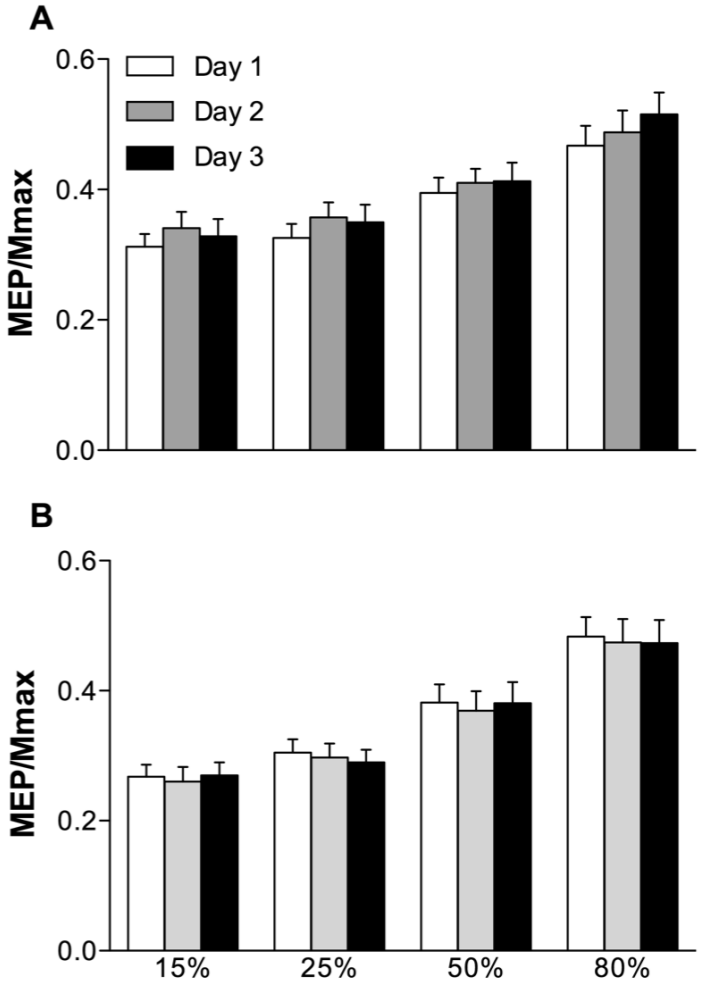

Figure 4.3 Motor evoked potentials day 1, 2, 3 at 15, 25, 50, and 80% of relative maximal voluntary contraction (MVC). **A** = Shortening, **B** = Lengthening.

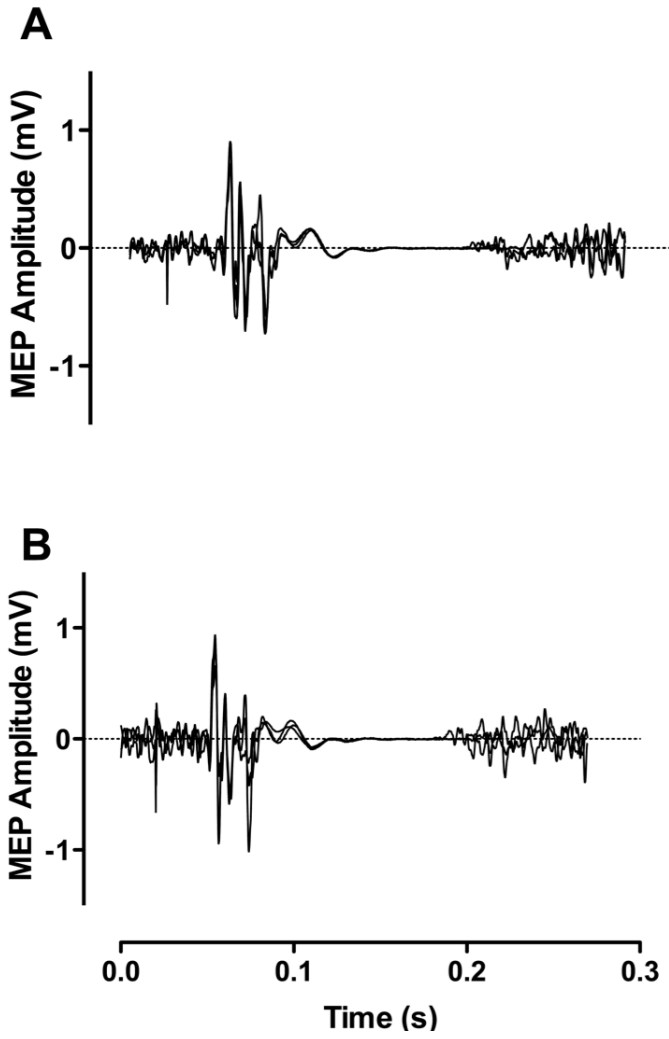

Figure 4.4 Representative traces of the cortical silent period for shortening (**A**) and lengthening (**B**) contractions at 80% of maximal voluntary contraction (MVC) are overlaid across the three days.

4.4 Discussion

Intrinsic oscillations in the CNS, methodological factors and muscle mechanics make TMS and PNS measures variable. This chapter presents new information focused on the stability of TMS and PNS measures during dynamic muscle contractions and establishes the error of measurement for future chapters. The main finding was that TMS and PNS measures revealed a high degree of repeatability during shortening and lengthening muscle contractions across three consecutive days. Variability in TMS

measures, evidenced by lower CV and reduced heteroscedasticity of the 95% CI, decreased from 2nd to 3rd day of testing particularly during rest, therefore a familiarisation session is advisable to improve repeatability; however, this trend is not apparent in PNS measures.

Previous research investigating the reliability of cortical responses in the TA has reported similar ICC values of 0.98 (Cacchio *et al.*, 2009) and 0.88 (Cacchio *et al.*, 2011) for rMT and resting MEP, respectively. Upper limb muscles have also revealed stable rMT between days (Malcolm *et al.*, 2006). It seems likely that the level of stimulation needed to excite the target muscle remains relatively consistent across repeated days. Despite the high ICC reported for resting MEP, the variability of the resting MEP between day 1-2 was relatively high (CV = 30%). Therefore, meaningful detectable changes in cortical excitability would need to be large to detect a worthwhile change. However, the variability significantly decreased between days 2 and 3 (CV = 16%), which make a familiarisation session essential. Consistent with previous studies, a single TMS session with multiple contractions can cause changes within M1 (Classen *et al.*, 1998; Kamen, 2004). In general, the TA is naturally accustomed to exercises that require smaller forces or resistance; the exposure in this study to higher intensity shortening and lengthening contractions was probably unfamiliar for the TA and therefore makes the expectation tenable that some degree of plasticity has occurred within M1. As the mere administration of TMS may also contribute to increased corticospinal excitability, (Kamen, 2004) it is likely that both the unaccustomed forceful contractions and TMS stimuli play a role in the increased variability and change in corticospinal excitability from day 1 to 2.

When compared to rest, this study suggests MEPs are more repeatable in an active muscle. With the exception of Kamen (2004), who showed a higher reliability during rest, assessing the motor cortex when the target muscle is activated appears to

stabilise MEPs (Devanne *et al.*, 1997; Carroll *et al.*, 2001). At rest, sensory inputs may influence the excitability of motor units in the pathway from M1 to the target muscle and thus potentially increase the variability of the MEP (Darling *et al.*, 2006). This is further supported with the body of research evidence showing changes in the size of the MEP through mental practice or imagery tasks (Kasai *et al.*, 1997; Yahagi and Kasai, 1998). Darling *et al*. (2006) suggested that the visual display of target torque reduced the variability through channelling the participants' attention to the required task. Although sensory inputs are important, it should be acknowledged that the sub-threshold motorneuron activity, which was consistent with previous studies, during isometric (Carroll *et al.*, 2001; Kamen, 2004) and dynamic contractions (van Hedel *et al.*, 2007), the results here demonstrated a trend toward poorer reliability and highest variability in MEPs at the higher intensities, particularly when the muscle was shortening. The high contraction intensities potentially cause larger desynchronisation of the compound action potential at the muscle membrane (Magistris *et al.*, 1999; Carroll *et al.*, 2001; Rosler, 2001). The intermittent arrival of the action potential at the muscle disrupts the 'shape' of the MEP through phase out cancellation (Rosler, 2001). Furthermore, compared to a lower intensity contraction, where torque is achieved through the intermittent activation of numerous motor units, the chance of a TMS pulse being discharged during the neuron refractory period during a high intensity contraction is increased because of greater synchronisation of motor units (Darling *et al.*, 2006). Although the results in this chapter support the work from Darling *et al*. (2006), where there was a stabilising effect of the MEP with a mild muscle contraction, the highest reliability was not at the lowest torque output for shortening or lengthening contractions, but at an intensity of 25% MVC. This is consistent with previous work showing higher repeatability during active dynamic muscle contractions at 20% compared to 10% MVC (van Hedel *et al.*, 2007). The exact reasons for this are unclear but may anecdotally be linked to the participants' motor ability to reach the required level of force at the higher (80%) and lower (15%) intensities during dynamic contractions, which is arguably more challenging.

Compared to previous work during isometric (Kamen, 2004) and dynamic contractions (van Hedel *et al.*, 2007), the results in this chapter have demonstrated that MEPs can be evoked with low variability between trials. Numerous methodological issues such as the selection of TA as the target muscle, the type of coil and number of stimuli given may account for higher reproducibility reported in the findings here compared to the previously discussed studies. Interestingly, when compared to lengthening muscle contractions, shortening contractions showed a poorer reliability at high contraction intensities. A reduced presynaptic synchronisation and a decrease in the probability of extra synchronous discharges during shortening contractions (Semmler *et al.*, 2002) could increase the amount of phase out cancelation and thus the variation in MEP amplitude during shortening contractions. Acute resistance training studies have shown a large increase in MEP size. For example, MEP_{MAX} has shown a 58% decrease (Jensen *et al.*, 2005), 38% increase (Kidgell *et al.*, 2010) and 58% increase after 6 days in the TA (Griffin and Cafarelli, 2007). It therefore seems logical to suggest that MEPs can be reproduced within an acceptable error to detect modifications during lengthening and shortening contractions.

The cortical silent period is thought to represent both spinal and intracortical inhibition (Wilson *et al.*, 1993; Ziemann *et al.*, 1996). One previous study has investigated the reliability of the cortical silent period during dynamic contractions (van Hedel *et al.*, 2007) and suggested that it was not repeatable under dynamic muscle contractions. However, the results from this chapter support the data from other work conducted under isometric conditions that the cortical silent period is a stable and repeatable TMS measure from day-to-day (Fritz *et al.*, 1997; Daskalakis *et al.*, 2003; Damron *et al.*, 2008; Saisanen *et al.*, 2008). Furthermore, there was no evidence of differences in the repeatability measures between shortening and lengthening muscle contractions at 80% MVC. As the cortical silent period is easily defined at high contraction intensities (Saisanen *et al.*, 2008) and is not affected by phase out cancelation in the same way as an MEP, it seems that the cortical silent period during 80% shortening and

lengthening MVC is highly reliable. Therefore, factors such as contraction intensity (Saisanen *et al.*, 2008) and method used to quantify the silent period (Damron *et al.*, 2008) might have a greater influence on the degree of reliability.

H-reflex is a reliable and well established method to assess spinal excitability at rest (Palmieri *et al.*, 2002; Mynark, 2005) and during isometric contraction (Chen *et al.*, 2010). The results here add to the limited research conducted during dynamic conditions (Simonsen and Dyhre-Poulsen, 2011) and showed only a small increase in variability when H-reflex is evoked during a dynamic contraction. Many studies examining muscles of the leg have predominantly focussed on the soleus and gastrocnemius rather than the TA, using PNS techniques, perhaps because of the ease to stimulate the tibial versus peroneal nerve. However, differences in the neuromechanics of muscle recruitment may also play an important role in the choice of muscle and therefore repeatability of the H-reflex. For example, the EMG response from transcutaneous stimulation of dorsal roots within the lumbosacral cord is higher in the soleus when compared to the TA (Troni *et al.*, 1996; Minassian *et al.*, 2007). Therefore, despite no differences in the site of stimulation, there is an apparent difference in recruitment strategies of the muscle that may contribute to the reduced repeatability of the TA when compared to the soleus. An additional possibility for the higher variability of H-reflex in the TA may reside with M_{MAX}. Although there was no significant difference in M_{MAX}, and a high degree of repeatability was also found (ICC = 0.66 – 0.72), the between trial ICC reported in previous work examining soleus and flexor carpi radialis was moderately higher (ICC $\geq$ 0.75) (Christie *et al.*, 2004; Christie *et al.*, 2005; Chen *et al.*, 2010). This may account for the greater variability in H-reflex, however interestingly, MEPs were also normalised to M_{MAX} and showed a very high degree of repeatability. This therefore suggests that H-reflex itself is a more variable measure from day-to-day in the TA.

The V-wave is often used as a measure of corticospinal drive (Aagaard *et al.*, 2002; Del Balso and Cafarelli, 2007; Fimland *et al.*, 2009a). Only one study has investigated its' day-to-day reliability (Solstad *et al.*, 2011). Solstad *et al*. (2011) showed that V-waves evoked during an isometric contraction of the gastrocnemius and soleus can be reliable from day-to-day (ICC = 0.92 and 0.86, respectively). The results in this chapter support this finding during shortening muscle contractions (ICC = 0.77) and to a lesser extent during lengthening contractions (ICC = 0.54). Notwithstanding the limitations of surface EMG (Farina *et al.*, 2004), V-wave is somewhat reliant on the antidromic action potential from the electrical stimulation that collides with the voluntary drive, but can also be influenced by motoneuron excitability and pre- and post-synaptic inhibition (Solstad *et al.*, 2011). Speculatively, the dynamic contractions used in this thesis may show a small, but nonetheless a greater, degree of variability in the collision or excitability of the motoneuron, although future research is required to elucidate underlying mechanisms of V-wave (Solstad *et al.*, 2011), particularly during different muscle contractions. Despite a high degree of error associated with V-waves during dynamic contractions, previous work has shown V-wave to increase in excess of 50%, post acute resistance training (Aagaard *et al.*, 2002). Therefore, it appears changes in V-wave are detectable in future chapters.

4.5 Conclusion

Although variation in intrinsic and methodological sources of error present a threat to the stability of TMS and PNS measures of excitability, this chapter has demonstrated that such measures are repeatable in the TA across three consecutive days. The data suggests greater repeatability and lower scedasticity from day 2 to day 3 than day 1 to day 2, therefore it seems prudent to include a familiarisation session to reduce the error associated with TMS measures in the TA, but this does not seem necessary for PNS measures.

4.6 Perspective

The initial aim of the thesis was to assess the reliability of TMS and PNS measures during shortening and lengthening muscle contractions. This chapter has demonstrated that TMS and PNS responses are repeatable, however due to the increase in resting MEP from day one to two a familiarisation session is needed. Furthermore, with a reduced error from days two to three compared to days one to two, all subsequent chapters in the thesis will familiarise participants 24 h before the initial assessment. Additionally, when clinicians and researchers are using TMS to assess the CNS, patients or participants should be familiarised the day before to avoid any misinterpretations of physiological variables. This chapter also suggests that clinicians assessing neurological conditions should consider performing TMS and PNS measure during dynamic muscle actions.

Chapter 5

Part I: Corticospinal and Spinal responses of resistance-trained and un-trained males during dynamic muscle contractions

5.1 Introduction

As discussed in section 2.5, morphological changes within the muscle account for some of the initial gains in strength associated with resistance training, although the predominant mechanism appears to be neurological adaptations within the CNS (Sale, 1988; Griffin and Cafarelli, 2005; Folland and Williams, 2007; Carroll *et al.*, 2011). An acute period of resistance training has been shown to increase the H-reflex (Aagaard *et al.*, 2002; Lagerquist *et al.*, 2006; Holtermann *et al.*, 2007; Duclay *et al.*, 2008) and V-wave (Aagaard *et al.*, 2002; Del Balso and Cafarelli, 2007; Duclay *et al.*, 2008). To further understand the effect of acute resistance training on corticospinal adaptations, a number of studies (Carroll *et al.*, 2002; Jensen *et al.*, 2005; Beck *et al.*, 2007; Griffin and Cafarelli, 2007; Schubert *et al.*, 2008; Carroll *et al.*, 2009; Hortobágyi *et al.*, 2009; Kidgell and Pearce, 2010) have used TMS to assess changes in cortical and spinal excitability/inhibition. However, despite the growing number of studies using TMS, research has not focused on modulation at multiple levels of the CNS in individuals with a history of resistance training. Consequently information regarding how the CNS supports the increased force generating capacity of trained muscle is unknown.

The exact nature and location of neurological adaptions that occur from chronic resistance training within the CNS (brain, spine or muscle) are not well understood. Using the interpolated twitch technique, a greater neural drive (38%) to the muscle in resistance trained individuals has been demonstrated (Fernandez del Olmo *et al.*, 2006), which appears independent from modulations in corticospinal excitability. However, these TMS responses (Fernandez del Olmo et al., 2006) were standardised to force and were not expressed relative to background electromyographic activity and hence not relative to the motoneuron pool. At a spinal level, a reduced H-reflex has been reported (Casabona *et al.*, 1990; Maffiuletti *et al.*, 2001) in strength/power athletes who engage in significant levels of resistance training, which is predominantly thought to be due to the transformation of fibre type from explosive ballistic movements (Koceja *et al.*, 2004). Furthermore, it is still not clear how the CNS is chronically

modulated to support the morphological adaptations at the muscle. The combination of TMS and peripheral nerve stimulation (PNS) may help to understand the site of adaptation and quantify how the muscle is supported at different levels of the CNS. Additional information on the paucity of data relating to the CNS responses in chronically resistance trained individuals may add greater clarity to whether adaptations in the CNS are an acute response to a previously unknown training stimulus, or a continuously evolving adaptation.

On first appearance, it could be argued that neurological adaptations in the TA may be limited. However, functional strength training (multiple joint exercises, including squat and bench press) has been shown to cause neural adaptations to single muscles in isolated contractions (Fimland *et al.*, 2009a). Therefore, it could be expected that even though the TA is not directly trained in a resistance training programme, a traditional functional resistance training will cause an increase in maximal torque in the TA. The unique accessibility and repeatability of the TA shown in Chapter 4 further enhances the justification for its use. Accordingly, the aim of the present study was to address the second aim of this thesis and compare corticospinal and spinal responses measured during dynamic muscle contractions of the TA in resistance trained and un-trained populations.

5.2 Methods

5.2.1 Participants

The study was approved by the University's Research Ethics Committee (RE07-01-12538) in accordance with the Declaration of Helsinki. Ten resistance trained (RT) and 9 un-trained (UT) males (mean ± SD age, stature and mass was 22 ± 2 and 26 ± 3 yrs, 178.2 ± 6.2 and 175.0 ± 5.9 cm, 87.8 ± 7.6 and 75.4 ± 6.6 kg, respectively) volunteered to take part in the study before undergoing health screening for neurological disorders and potential adverse effects from TMS (described in section 3.2.2) and providing written informed consent. The RT group had a history of no less than 3 years of heavy

load resistance training exercise, consisting of 3 or more training sessions per week. The UT group was sedentary individuals. The TA of the dominant leg was assessed in both groups, 18 of the 19 participants were right leg dominant. Participants were told to refrain from caffeine on the day, avoid alcohol within 24 h and refrain from eating 1 h prior to testing.

5.2.2 Study Design

Participants visited the laboratory on two consecutive days completing an identical protocol. Based on the results from Chapter 4, participants completed the full protocol on day one as the familiarisation session. TMS and PNS responses between groups were compared on day two. TMS responses were recorded at rest and during shortening and lengthening muscle contractions (15, 25, 50, 80% of maximal voluntary contraction). Additionally, PNS responses were recorded at rest and during shortening and lengthening maximal voluntary contractions and 25% MVC. The presentation of contraction intensity (15, 25, 50, 80% of maximal voluntary contraction), type (shortening and lengthening) and order (TMS and PNS) were randomised.

5.2.3 Experimental Set-up

For experimental set up, please see ‘General Methods’ section 3.2.4.

5.2.4 Maximal Voluntary Contraction

MVC was recorded for shortening, lengthening and isometric contractions at the beginning of the familiarisation testing session. This was verified at the beginning of the main trial. For full procedure of MVC, see ‘General Methods’ section 3.2.6.

5.2.5 Surface Electromyography (EMG)

For electromyography, please see ‘General Methods’ section 3.2.4.

5.2.6 TMS Protocol

Section 3.2.7 describes the method used to establish the 'hotspot', resting motor threshold (rMT) and resting MEP. All TMS stimuli were delivered at 120% rMT. The order of contraction (lengthening and shortening) and intensity (80, 50, 25, 15% MVC) were randomised and counterbalanced. Furthermore, the order of TMS and PNS was randomised. TMS responses were averaged from eight responses and all contractions were separated by 25 s (Chapter 3, Part II). The corticospinal silent period was recorded at 80% MVC. Analysis of the silent period is described in 'General Methods' section 3.2.7.

5.2.7 Peripheral Electrical Stimulation Procedure

For detailed description of PNS, see 'General Methods' section 3.2.7. Briefly, a H-M recruitment curve was established under a 10% isometric contraction. Following this, H-reflex was recorded during 25% shortening and lengthening MVC. Finally, V-waves were recorded during maximal shortening and lengthening muscle contractions.

5.2.8 Data Analysis

Variables were recorded within a 500 ms window. This included 50 ms before stimulation to capture pre stimulus EMG. Corticospinal and spinal reflexes were analysed off-line (Signal v3.0, Cambridge Electronic Design, Cambridge, UK). MEPs, H-reflex and V-waves peak-to-peak amplitudes were normalised to peak-to-peak M_{MAX}. Corticospinal and spinal variables were also reported relative to background EMG and M_{MAX}. When expressed relative to background EMG activity, EMG was rectified with the mean muscle activity 25 ms following the stimulator artefact. Similarly, MEPs were expressed relative to the torque and M_{MAX}. MEPs during this condition were averaged over 25 ms from the initial appearance, whilst the duration of the cortical silent period was measured from the stimulator artefact to a return of 1 SD of pre-stimulus EMG.

5.2.9 Statistics

All variables are expressed as mean ± SD. To detect differences between groups (RT vs. UT) for MEP amplitude, a two-way analysis of variance was used (ANOVA) – Group (RT, UT) by intensity (15, 25, 50, 80%). The ANOVA was repeated for each contraction type (Shortening and Lengthening). Additionally, between group differences for all other corticospinal and spinal variables were assessed with a two-way ANOVA (group × contraction type). To ensure there were no differences in relative torque between groups, a two-way ANOVA was conducted. Any significant interactions were followed up using the LSD *post-hoc* pairwise comparisons with 95% CI. Significance was accepted as $P < 0.05$.

5.3 Results

The RT group were stronger compared to the UT group ($F_{(1,17)} = 6.6$: $P = 0.02$). *Post-hoc* comparisons revealed the RT group were significantly stronger during shortening, (28%; $P = 0.023$: CI = 1.27 – 15.1 N·m), lengthening (25%; $P = 0.041$: CI = 0.27 – 17.0 N·m) and isometric (20%; $P = 0.041$; CI = 0.77 – 14.9 N·m) muscle contractions. There were no differences in relative torque between groups at any condition (Table 5.1).

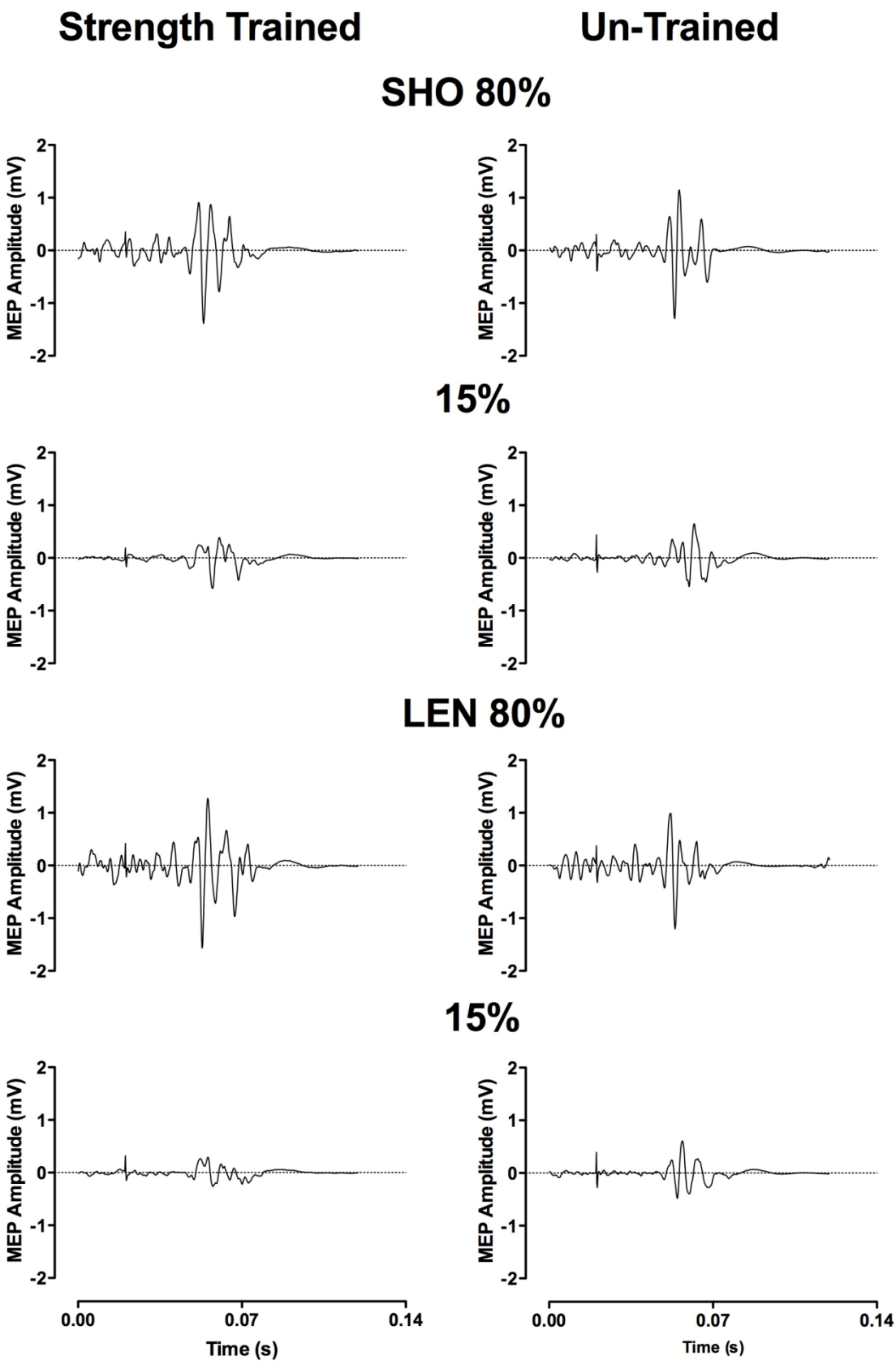

Figure 5.1 A representative trace of motor evoked potentials at 15 and 80% of relative maximal voluntary contractions from a strength trained and un-trained individual. SHO = Shortening, LEN = Lengthening,

Table 5.1 Force (% MVC) during different shortening and lengthening contraction intensities during TMS and PNS (mean ± SD).

	TMS								PNS	
	SHO	**LEN**	**SHO**	**LEN**	**SHO**	**LEN**	**SHO**	**LEN**	**SHO**	**LEN**
	Target Torque (%)									
	15		25		50		80		25	
RT	15.7 ± 3.22	18.2 ± 3.96	28.1 ± 6.65	28.2 ± 6.10	52.4 ± 6.63	47.6 ± 7.87	75.9 ± 8.65	76.3 ± 11.9	24.7 ± 4.72	24.4 ± 7.79
UT	16.6 ± 4.71	19.0 ± 2.64	26.2 ± 5.51	28.9 ± 4.85	48.3 ± 9.19	50.0 ± 8.71	76.1 ± 10.8	75.9 ± 10.4	25.3 ± 3.79	27.8 ± 5.13

RT; Resistance-Trained, UT; Untrained, TMS; Transcranial Magnetic Stimulation, PNS; Peripheral Nerve Stimulation, ISO; Isometric, SHO; Shortening, LEN; Lengthening.

Table 5.2 MEP relative to Torque during different shortening and lengthening contraction intensities during TMS and PNS (mean ± SD).

	TMS								PNS	
	SHO	**LEN**	**SHO**	**LEN**	**SHO**	**LEN**	**SHO**	**LEN**	**SHO**	**LEN**
	M_{MAX} (%)									
	15		25		50		80		25	
RT	7.16 ± 5.50	2.85 ± 1.67	3.98 ± 2.44	2.05 ± 1.01	2.38 ± 1.23	1.64 ± 0.91	1.81 ± 0.88	1.49 ± 0.86	1.73 ± 1.14	0.77 ± 0.22
UT	7.05 ± 3.21	3.21 ± 0.99	4.74 ± 2.26	2.42 ± 1.01	2.85 ± 0.92	1.75 ± 0.73	2.36 ± 1.09	1.42 ± 0.57	1.70 ± 0.69	0.95 ± 0.47

RT: Resistance-Trained, UT; Untrained TMS, Transcranial Magnetic Stimulation; PNS, Peripheral Nerve Stimulation; ISO, Isometric; SHO, Shortening; LEN, Lengthening

There were no significant differences in resting MEP as a percentage of M_{MAX} (RT = 9.6 ± 7.1 Vs UT = 8.9 ± 7.8%; P = 0.60) or rMT (RT = 43 ± 8.2 Vs UT = 47 ± 6.2% P = 0.07). A representative trace of MEPs for a RT participant and an UT participant at high and low contraction intensity is shown in Fig 5.1. MEPs and H-reflex amplitudes were consistent with previous literature (Morita *et al.*, 2000). No significant differences in MEPs (P = 0.53) or MEPs when expressed relative to background EMG (P = 0.88) were found between groups (Fig. 5.2). Similarly, there was no significant difference (P = 0.79) between groups when MEP's were expressed relative to torque. The cortical silent period was not different between groups (P = 0.51) during shortening (RT = 168 ± 39 Vs. 157 ± 36 ms) and lengthening (RT = 180 ± 43 Vs. 164 ± 44 ms) muscle contractions.

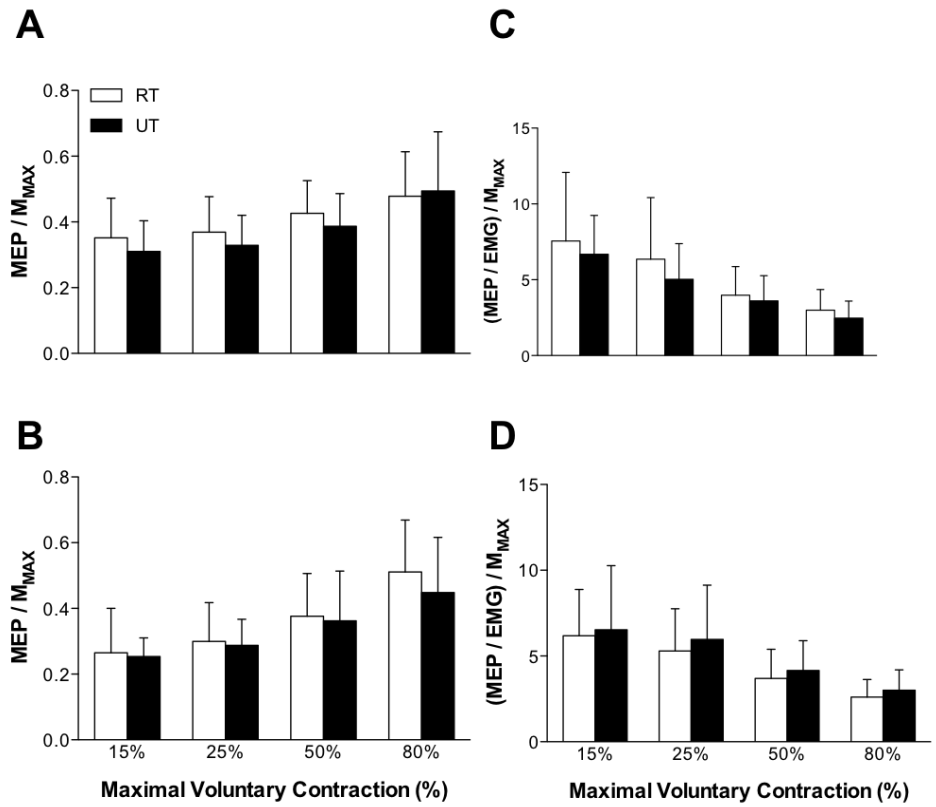

Figure 5.2 Motor evoked potentials in strength trained (RT) and un-trained (UT) individuals at 15, 25, 50, and 80% of relative maximal voluntary contraction (MVC). **A** = Shortening muscle contractions relative to M_{MAX} **B** = Lengthening muscle contractions relative to M_{MAX}. **C** = Shortening muscle contractions relative to M_{MAX} and background EMG. **D** = Lengthening muscle contractions relative to M_{MAX} and background EMG.

No significant differences were found between groups for H_{MAX}/M_{MAX} (P = 0.25), even when relative to background EMG (P = 0.53; Fig.5.3). Similarly, no differences were found between groups for V-wave when relative to background EMG (P = 0.36) or solely M_{MAX} (P = 0.75; Fig. 5.4).

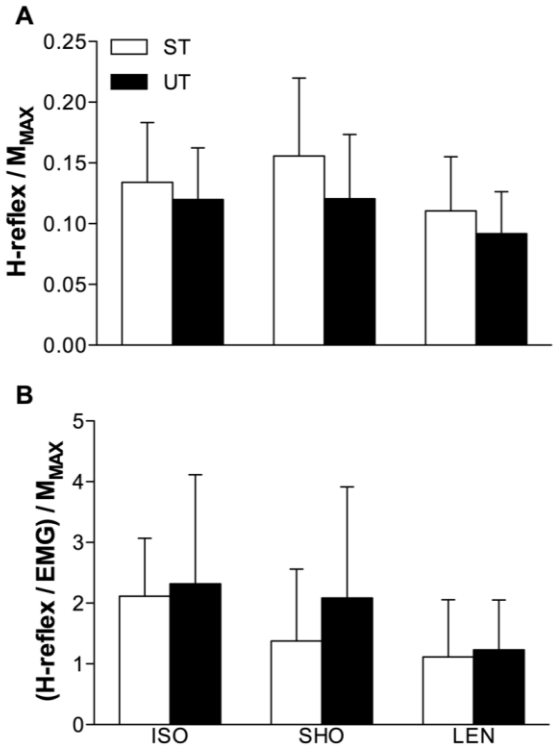

Figure 5.3 H-reflex during isometric (ISO), shortening (SHO) and lengthening (LEN) muscle contractions**. A** = H-reflex relative to M_{MAX}. **B** = H-reflex relative to M_{MAX} and background EMG.

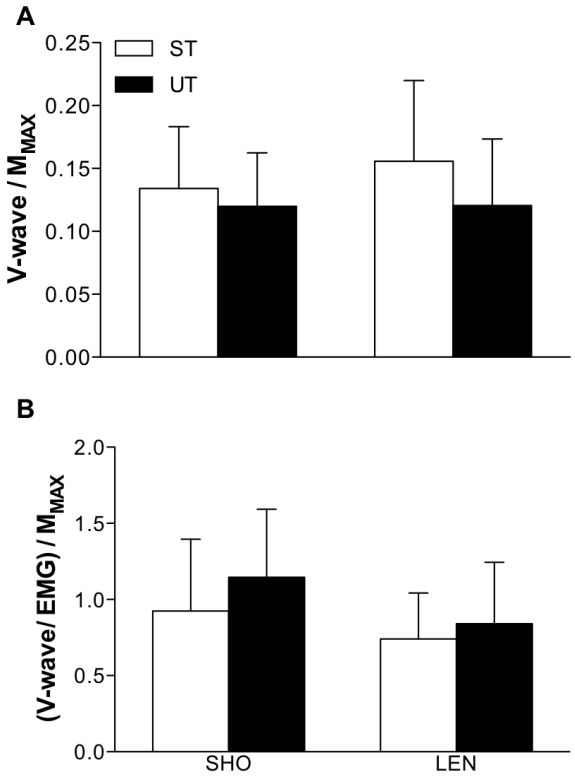

Figure 5.4 V-wave during shortening (SHO) and lengthening (LEN) maximal voluntary contractions **A** = V-wave relative to M_{MAX}. **B** = V-wave relative to M_{MAX} and background EMG.

5.4 Discussion

The aim of this chapter was to compare corticospinal and spinal responses measured during dynamic muscle contractions of the TA in RT and UT individuals. The findings revealed there were no differences in corticospinal or spinal responses between the RT and UT groups even when expressed relative to neural output (background EMG) and torque. The lack of differences may be linked to the specific training status of the TA muscle through minimal exposure to isolated high intensity resistance training.

Despite higher MVCs across all contraction types, there were no discernable differences in corticospinal excitability (MEPs) between the RT and UT groups across contraction types. The lack of differences in corticospinal excitability supports the only previous study in the area (Fernandez del Olmo *et al.*, 2006), but adds new information demonstrating, when relative to neural output, there are still no detectable differences

between groups. Whilst Fernandez del Olmo *et al*. (2006) suggest the non-significant differences reported may be linked to poor reproducibility of MEPs, however, data from this thesis has shown that MEPs have a high degree of reproducibility during dynamic contractions (Tallent *et al.*, 2012).

Previous research demonstrating an increase in cortical excitability in highly skilled racquet sports players compared to UT social players (Pearce *et al.*, 2000) suggests that changes in cortical excitability may be linked to skill training or acquisition of a skill. Initial gains in strength are due to improved motor control of a task (Sale *et al.*, 1983a; Rutherford and Jones, 1986), however, long-term adaptations to resistance training may reside at a spinal level. In support of this, Adkins *et al*. (2006) used electron microscopy to reveal that at a spinal level, there was a significant synaptogenesis from resistance training that was not evident in a skill only group. Additionally, relatively simple but well learned tasks have a minor influence on the organisation of the motor cortex (Plautz *et al.*, 2000), with the level of force (large vs. small) performed in a trained movement shown to have no effect on the magnitude of cortical activity (Remple *et al.*, 2001). It is plausible that changes in corticospinal excitability found in acute resistance training studies (Carroll *et al.*, 2002; Griffin and Cafarelli, 2007; Kidgell *et al.*, 2010; Weier *et al.*, 2012) may be associated with motor learning rather than the early stages of resistance training. Therefore, the lack of difference in cortical responses found in this chapter supports the notion that resistance training adaptations might reside at a spinal level. Further research that focuses on muscles specifically targeted in resistance exercise, and that are well trained, is warranted to confirm these findings. It could be argued that the TA is not a good candidate muscle to assess chronic RT adaptations because it is generally not a specifically targeted muscle in resistance training regimens.

This study compared the length of the cortical silent period in chronically RT and UT individuals. The first 50 ms phase of the silent period is considered to be due to spinal

sources and the latter is the result of intracortical inhibition (Wilson *et al.*, 1993; Ziemann *et al.*, 1996; Chen *et al.*, 1999). Whilst there is no research comparing RT to UT, there is evidence showing highly skilled individuals have a similar length cortical silent period to their un-trained counterparts (Pearce *et al.*, 2000). One previous study has demonstrated a reduction in the cortical silent period from acute resistance training (Kidgell and Pearce, 2010); the authors suggested adaptations were due to reduced inhibition in the motor cortex and spinal cord. Although this study examined differences between groups (whereas Kidgell and Pearce, 2010 examined the cortical silent period pre to post training), it does offer further information that resistance training might not cause changes in corticospinal inhibition silent period.

Despite a reduced rMT reported in the dominant hand of highly skilled individuals (Pearce *et al.*, 2000), previous work in the bicep brachii has shown no relationship between rMT and resistance training status (Fernandez del Olmo *et al.*, 2006). An obvious difference between the skill and strength training research is the use of the contralateral hand as the control rather than a control group and may lead to the argument of selection bias. However, due to an increase in contralateral strength in the homologous muscle (Hortobágyi *et al.*, 1997; Farthing and Chilibeck, 2003), it is not possible for the subjects to serve as their own control. Furthermore, due to the predominantly bilateral nature of resistance training, adaptations will not be limited to one side of the body.

The current investigation combined corticospinal and spinal responses between RT and UT individuals in a single session, however, in contrast to previous work (Casabona *et al.*, 1990; Nielsen *et al.*, 1993), the results in this chapter showed no differences in spinal excitability between RT and UT individuals. One obvious difference between the aforementioned studies is the muscle under investigation. In the plantar flexors, power trained athletes have reported a shift towards fast-twitch muscle fibres (Clarkson *et al.*, 1980). As fast twitch muscle fibres are less excitable

than slow twitch muscle fibres in the Ia afferent volley (Almeida-Silveira *et al.*, 1996), a lower H-reflex has subsequently been reported (Casabona *et al.*, 1990; Nielsen *et al.*, 1993). Whether the TA is susceptible to the same shift in muscle type distribution is debatable and consequently may explain the lack of detectable differences between the two groups. Furthermore, lower presynaptic inhibition reported in RT athletes has been suggested to cause increased spinal excitability in RT individuals (Earles *et al.*, 2002). A combination of no shift in muscle fibre distribution and decrease in presynaptic inhibition might contribute to the lack of differences found between groups. Furthermore, adaptations such as synaptogenesis that are undetectable through changes in H-reflex excitability cannot be excluded and may account for the increase in strength found in the RT group.

Increases in V-wave with resistance training are associated with an increased efferent output during MVCs (Aagaard *et al.*, 2002). From acute resistance training, V-wave studies have shown to increase in excess of 50% from baseline values (Del Balso and Cafarelli, 2007; Fimland *et al.*, 2009a), however, knowledge of the responses in resistance trained athletes is limited (Upton and Radford, 1975; Sale *et al.*, 1983b). Whilst there is evidence to suggest that functional resistance training causes adaptations in single muscle tasks (Fimland *et al.*, 2009a), the results here suggest that the TA shows no increase in efferent output during MVCs. Increase in V-waves have been reported in weightlifters (Upton and Radford, 1975) and sprinters (Sale *et al.*, 1983b), however, adaptations appear to be muscle specific. For example, responses in thenar muscles were similar between groups. As the thumb adductors are used extensively in everyday tasks, the authors suggested both groups might have been equally trained in this muscle. The RT group in this chapter was significantly stronger in all muscle contractions, arguably due to the aforementioned history of resistance training. However, whether this resides in a higher efferent output appears unlikely. The corticospinal projections to the TA are easily activated in comparison to other lower extremity muscles (Morita *et al.*, 2000) to ensure precision when the toe

clears the floor through the gait cycle (Petersen *et al.*, 2003); the influence these unique characteristics have on the neurological plasticity of the TA from resistance training is unknown.

5.5 Conclusion

There were no detectable differences in corticospinal or spinal responses between RT and UT individuals. From a cortical perspective, the data here supports previous research showing no change in cortical excitability in RT individuals and have presented new observations that demonstrated similar cortical inhibition between RT and UT individuals. In contrast to previous work, there were no detectable neurological adaptations at a spinal level either. Whether the TA is exposed to the same shift in muscle type distribution from RT remains debatable and consequently may explain the lack of detectable differences in spinal variables between groups. Future research investigating TMS and PNS responses of chronically trained individuals should continue to focus on adaptations at multiple levels of the CNS in a single session, but attention should be directed towards muscles that are targeted in a traditional resistance training programme.

5.6 Perspective

The secondary aim of the thesis was to examine the TMS and PNS responses in chronic resistance trained and untrained individuals during shortening and lengthening muscle contractions. It appears that chronic resistance training does not alter TMS or PNS responses in chronic resistance trained individuals in the TA. The results from Chapter 4 showed an increase in corticospinal excitability 24 h following exposure to multiple shortening and lengthening muscle contractions. Surprisingly, this acute change was not evident in chronic resistance trained individuals. Logically, the lack of differences between the two groups may be due to the lack of training stimulus in the TA. However, the RT group showed a greater force producing capacity of the muscle suggesting there is some form of neurological adaptation. This may be linked to the

variability of the neurological drive from the motor cortex to the muscle, therefore the data from this study needs further investigation to assess if there is some modification in the CNS between the trained and untrained individuals.

Part II: Variability of Corticospinal responses of resistance-trained and un-trained males during dynamic muscle contractions

5.7 Introduction

Short-term adaptations from RT have been repeatedly shown to improve force accuracy (Hortobágyi *et al.*, 2001; Tracy *et al.*, 2004; Kornatz *et al.*, 2005) through mechanisms such as a reduction in motor unit discharge variability (Kornatz *et al.*, 2005). When compared to un-trained individuals, RT individuals have demonstrated a more stable torque during maximal contraction that is not evident during lower torque outputs (Smits-Engelsman *et al.*, 2008). How the CNS modulates to improve this motor output consistency is unclear. However, RT individuals have demonstrated an increased motor-unit coherence through a more efficient activation of the task related neurons (Semmler *et al.*, 2004). Therefore, the possibility exists that neurological output is less variable in RT individuals when compared to un-trained individuals.

Wise *et al*. (1998) reported that retrieval and modification of a previous motor task is associated with a more rapid increase in performance on a visual-motor task when compared to the creation of new motor patterns. RT individuals acquire many different motor programmes from years of training and have the potential to retrieve and adapt an existing motor programme. Therefore, it is hypothesised that RT individuals will show a greater degree of plasticity through a more consistent MEP evoked during a motor control task repeated 24 h after an initial bout.

The second part of this section will further explore the data and compare corticospinal responses to determine the effects of training status on MEP variability, with the aim to compare MEP variability and the change in variability after a familiarisation session.

5.8 Methods

5.8.1 Study Design

Data were re-examined from Part 1 of this study. As participants repeated the same protocol on two consecutive days, variability of MEPs was compared on day 1 (familiarisation) and changes between days 1 and 2 were also examined.

5.8.2 Data Analysis

Variability of MEPs was calculated as the CV from the 8 stimuli.

5.8.3 Statistics

All variables are expressed as mean ± SD. To detect differences between groups (RT vs. UT) for MEP amplitude and variability CV at the range of contraction intensities, a two-way analysis of variance was used (ANOVA) – Group (RT, UT) by intensity (15, 25, 50, 80%). The ANOVA was repeated for each contraction type (Shortening and Lengthening). Changes in MEP variability from day 1 to 2 for each group was assessed with an ANOVA (day × intensity) for each contraction type. Changes in MEP variability at rest from days 1 to 2 was assessed with an independent samples *t*-test. Differences of within-day variability on day 1 were assessed with a two-way ANOVA (group × intensity). Any significant interactions were followed up using the LSD *post-hoc* pairwise comparisons with 95% CI. Significance was accepted as $P < 0.05$.

5.9 Results

No significant difference in MEP variability on day 1 was found between groups during rest, shortening or lengthening muscle contractions ($P > 0.05$). There was no significant change in MEP variability from day 1 to 2 in the UT group or the RT group during shortening or lengthening contractions ($P > 0.05$). However, the RT participants showed a significant reduction in resting MEP variability from day 1 to 2 ($t_{(9)} = 3.68$; 5.45 – 22.8%: $P = 0.01$: Fig. 5.5) that was not evident in the UT group ($P = 0.62$).

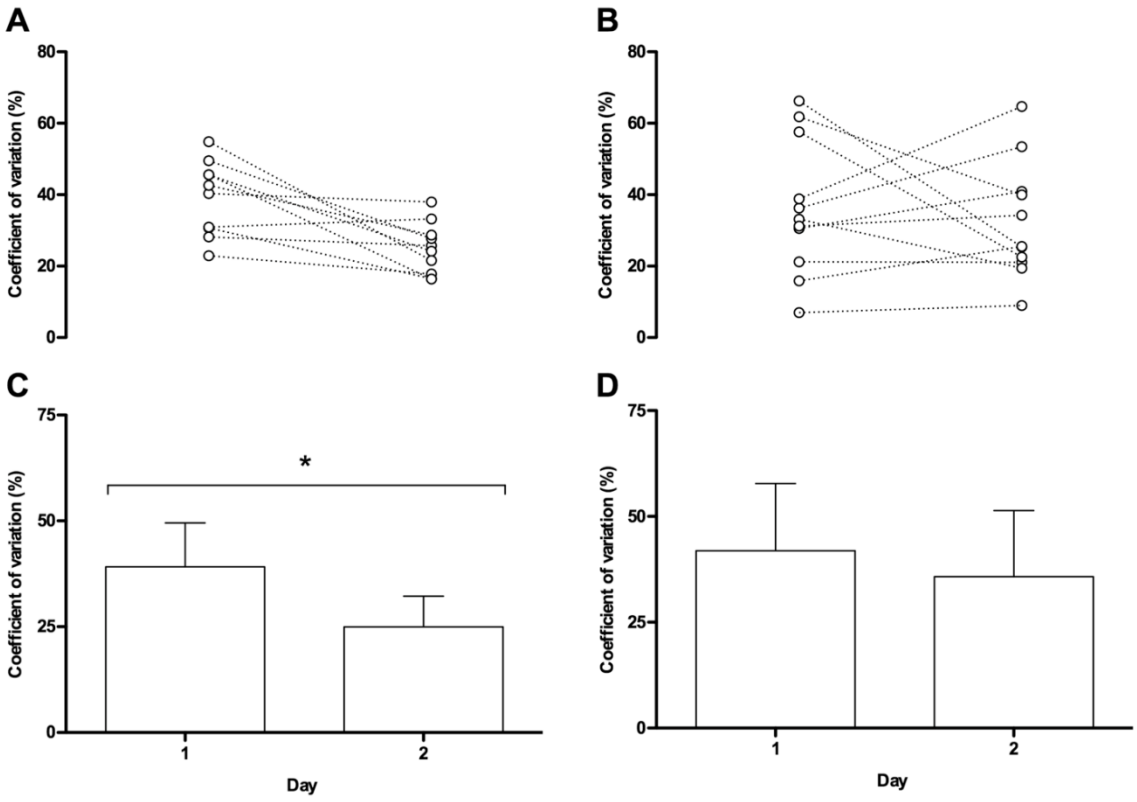

Figure 5.5 Individual and mean coefficient of variations (CV) of 8 resting motor evoked potentials (MEPs) from day 1 to 2. **A =** Individual CV from days 1 to 2 in the resistance-trained group (RT). **B =** Individual CV from days 1 to 2 in the un-trained group (UT). **C =** Mean CV from days 1 to 2 in the RT group. **D =** Mean CV from days 1 to 2 in the UT group. *(P = 0.016).

5.10 Discussion

As previously discussed, the lack of differences in MEP variability between groups may be linked to the specific training status of the TA muscle. These data illustrate RT individuals have a more consistent corticospinal response following a familiarisation session, however, it is unclear why this was only evident at rest.

Numerous researchers have demonstrated that MEPs vary between pulses (Kiers *et al.*, 1993; Ellaway *et al.*, 1998) due to constant oscillations in the CNS. Cortical fluctuations on the spinal motorneurons are believed to be the cause of stimuli-to-stimuli variability (Ellaway *et al.*, 1998). Factors such as a shift towards type II muscle

fibres and increased synchronisation of motor units from long term ballistic resistance training have the potential to cause larger force fluctuations when compared to UT individuals (Smits-Engelsman *et al.*, 2008). However, the lack of differences in motor output consistency previously reported between RT and UT individuals (Smits-Engelsman *et al.*, 2008) indicate that the CNS may be modulated to control large force fluctuations through a more consistent efferent output. Furthermore, less motorneuron synchronisation has the ability to cause an increased amount of phase-out cancellation and thus contribute to MEP consistency from stimuli to stimuli (Rösler *et al.*, 2008). Conversely, the findings in this chapter suggest that there is little difference in MEP variability between the RT and UT individuals. Despite previous reports of improved output consistency during high intensity contraction in RT when compared to UT individuals (Smits-Engelsman *et al.*, 2008), there was no evidence of a reduced MEP variability during the familiarisation session. A logical explanation for the lack of differences between the two groups may be the specificity of the task to RT individuals. Participants were asked to perform shortening and lengthening isokinetic muscle contractions at different contraction intensities in a muscle that is not specifically targeted in RT. Arguably, these tasks are unfamiliar to both groups and this could explain the similarity found between groups.

For the first time, data regarding the change in MEP variability after a familiarisation session in RT and UT trained individuals are reported here. Supporting the hypothesis, there was a reduction in MEP variability from session 1 to 2 but only in the RT individuals. This evidence suggests the CNS of RT individuals has a greater degree of plasticity compared to UT. It has been suggested that spinal motorneurons recruited from the TMS evoke descending drive and the number of activated motorneurons is the fundamental cause of MEP variability (Rösler *et al.*, 2008). It is difficult to speculate the exact mechanism responsible for the reduction in variability between trial 1 and 2; however, increased motor unit synchronisation (Dartnall *et al.*, 2008) and a reduction in motor unit threshold (Dartnall *et al.*, 2009) have been reported 24 h following

lengthening muscle contractions which may provide some insight. Even though the protocol used by Dartnall *et al*. (2009) was severe, damaging exercise, the increase in motor unit synchronisation and discharge rate from immediately post to 24 h post exercise demonstrates the rapid plasticity of the CNS. Furthermore, Baker *et al*. (2001) suggested that resistive exercise tasks require accuracy, and synchronisation of the motorneuron and is modulated at a cortical level. It is therefore speculated that the reduction in MEP variability in the RT group was due to greater plasticity of the motor cortex to synchronise the descending action potential; however, the exact mechanisms remain to be elucidated.

5.11 Conclusion

In conclusion, there were no detectable differences in corticospinal responses between RT and UT individuals. From a cortical perspective, the data supports previous research showing no changes in cortical excitability in RT individuals and furthermore, new data has been presented demonstrating similar cortical inhibition between RT and UT individuals. In contrast to previous work, there were no detectable neurological adaptations at a spinal level. Whether the training stimulus is sufficient in a conventional resistance training programme to cause a shift in muscle fibre type distribution is debatable and consequently may explain the lack of detectable differences in spinal variables between groups. In addition, new data presented here suggested RT individuals showed a more consistent neurological response following a familiarisation session. The differences can arguably be attributed to a greater synchronisation of the action potential at a cortical level. However, why these differences were only evident during resting conditions is unclear.

5.12 Perspective

The overall aim of this chapter was to explore differences in TMS and PNS responses between chronic resistance trained and untrained individuals. Whilst there were no detectable differences in TMS and PNS responses, part II of this chapter suggested a

greater CNS plasticity in resistance trained individuals, evidenced by variability in MEP response from day 1 to day 2. Therefore, it was concluded that changes in corticospinal excitability, inhibition, H-reflex and V-wave contribute little to the force generating capacity of the TA in resistance trained individuals. Additionally, synchronisation shown through variability of the MEP appears to be negligible. The chapter showed data that warrants further investigation; but importantly for practitioners that the CNS may show a greater degree of plasticity to new motor patterns that could manifest as improved movement control during the assessment.

Chapter 6

Part I: Corticospinal and Spinal Responses to Shortening and Lengthening Resistance Training

6.1 Introduction

The previous chapter has shown no detectable differences in TMS and PNS responses between chronic resistance trained and untrained individuals. Similarly to chronic neurological adaptations to resistance training, little is known of the exact neurological mechanisms responsible for acute increases in force generating capacity of the muscle, particularly in regard to shortening and lengthening resistance training. Maximising acute neurological adaptations from resistance training is an important aspect to improve muscle function in older adults, clinical populations, athletic performance and rehabilitation programmes (Folland and Williams, 2007; Isner-Horobeti *et al.*, 2013).

However, despite the large body of research focusing on the early neurological adaptations to resistance training, there are discrepancies regarding the neurological mechanisms responsible for the muscle to increase the force generating capacity. The contributions (summarised in reviews: (Carroll *et al.*, 2011; Kidgell and Pearce, 2011) using TMS and PNS have developed our understanding of the neuromuscular adaptations to resistance training, particularly within the CNS. An increase in corticospinal excitability (Griffin and Cafarelli, 2007) and reduced inhibition (Kidgell and Pearce, 2010; Kidgell *et al.*, 2010; Weier *et al.*, 2012) have been reported following a period of acute resistance training. However, there is conflicting evidence that has shown no change in corticospinal inhibition (Kidgell *et al.*, 2010) and reduced or no change in MEP peak-to-peak amplitude post-resistance training (Carroll *et al.*, 2002; Jensen *et al.*, 2005; Carroll *et al.*, 2009). Furthermore, at a spinal level, an increased spinal excitability has been reported in some studies (Aagaard *et al.*, 2002; Gondin *et al.*, 2006a), but not others (Holtermann *et al.*, 2007; Ekblom, 2010); however, V-wave has consistently been shown to increase as a result of resistance training (Aagaard *et al.*, 2002; Gondin *et al.*, 2006a; Ekblom, 2010). Thus, using these techniques in concert

throughout one study will allow a greater understanding of the brain-to-muscle pathway and provide information on early adaptive responses to resistance training.

Resistance training programmes consist predominantly of shortening and lengthening muscle contractions. Lengthening contractions have been shown to have a positive influence on stroke patients, (Engardt *et al.*, 1995) in cardiovascular disease (Meyer *et al.*, 2003) and diabetics (Marcus *et al.*, 2008). In an athletic setting, lengthening contractions have been associated with a reduction in injury (Jonhagen *et al.*, 1994) and an improvement in dynamic movements (Clarka *et al.*, 2005). Therefore understanding these dynamic contractions is vital for the practices of applied sport scientists and clinicians. Factors such as a reduced metabolic cost (Gondin *et al.*, 2006a), unique control strategies (Duclay *et al.*, 2011), higher cortical output (Fang *et al.*, 2004) and greater increase in total strength (Roig *et al.*, 2009) during and following lengthening muscle contractions (compared to shortening) further illustrate the importance of lengthening muscle contractions to resistance training and rehabilitation programmes (Isner-Horobeti *et al.*, 2013).

It is unknown if the higher absolute loads lengthening muscle contractions can tolerate provide a greater stimulation for the neurological system, or whether the unique motor control strategies have a greater potential for neurological adaptation. Evidence from Hortobágyi *et al.* (1996) demonstrated that lengthening muscle training contractions increased neurological output seven times more during lengthening contractions compared to shortening muscle contractions from shortening resistance training, which was accompanied by a 3.5-fold increase in strength. Predominantly, the body of literature fails to support the notion of a greater increase in EMG from lengthening resistance training (Higbie *et al.*, 1996; Blazevich *et al.*, 2008) and only a few studies have shown evidence of a contraction-mode specific neurological adaptation (Higbie *et*

al., 1996; Hortobágyi *et al.*, 1996). Even though control strategies differ between contraction types at a cortical and spinal level, no study has assessed changes in neurological adaptations following lengthening and shortening resistance training. Segmentally assessing adaptations at the supraspinal and spinal level will contribute to our understanding of the greater strength and neurological adaptations proposed from lengthening muscle action resistance training.

Consequently, the purpose of this study was to address the final aim of this thesis and investigate the acute (4 weeks) TMS and PNS responses from shortening and lengthening resistance training and subsequent detraining. The detraining aspect will be discussed in Part II of this chapter.

6.2 Methods

6.2.1 Participants

Following institutional ethical approval (SUB53_JT_0211) in accordance with the Declaration of Helsinki, 31 volunteers completed a health screening questionnaire and provided written, informed consent. Participants had no structured resistance training history in the preceding two years and were randomly assigned to either a shortening resistance training (SHO (n = 11)), lengthening resistance training (LEN (n = 11)) or a control (CON (n = 9)) group (mean ± SD age, stature and mass was 24 ± 3, 24 ± 3 and 27 ± 4 yrs, 175.9 ± 10.6, 176.3 ± 9.6, 172.7 ± 8.5 cm and 77.1 ± 10.2, 75.7 ± 12.3, 74.7 ± 11.1 kg, respectively). As in previous chapters, the TA muscle was used to examine adaptations to resistance training. Participants were asked to refrain from any form of resistance training throughout the duration of the study. Of the 32 participants, 29 were right limb dominant. Preliminary power analysis using GraphPad StatMate (v5.0, San Diego, CA, USA), and previous work (Hortobágyi *et al.*, 1997; Hortobagyi *et al.*, 2000),

revealed that to achieve a power of 0.80 (α = 0.05), 10 participants per experimental group were needed. However, as no participants withdrew from the study, the experimental groups consisted of 11 subjects in each individual experimental training group.

6.2.2 Study Design

The initial four weeks consisted of resistance training and then two weeks detraining in the experimental group, with the CON group remaining inactive throughout the six weeks. Part II of this chapter will discuss the role of detraining following the four weeks resistance training. Figure 6.1 outlines the 4 week training and 2 week detraining protocol.

Participants allocated to the resistance training group reported to the laboratory on 17 separate occasions (five for assessment and 12 for training sessions); the CON group conducted the five assessments only. All participants performed a familiarisation session 24 h before pre testing assessment. Midpoint assessment was conducted after two weeks (following six training sessions) and post training assessment was after 4 weeks (12 training sessions). Final measures were taken after 2 weeks of detraining (weeks 5 and 6) and are discussed in part II of this chapter.

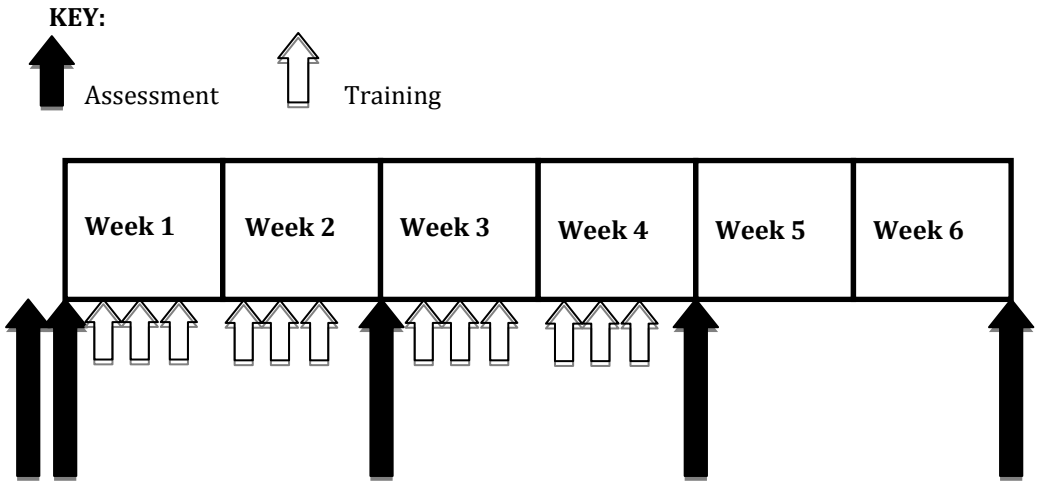

Figure 6.1 Schematic outlining weeks 1-4 of the training protocol (Part I) and weeks 5 and 6 of the detraining (Part II).

6.2.3 Experimental Set-up

MVC, TMS and PNS related measures were recorded using previously described methods in section 3.2.4. Muscle thickness was recorded at the start of each assessment session to detect changes in muscle thickness (see 'section 6.2.5 Ultrasound' for method).

6.2.4 Maximal Voluntary Contraction

MVC of the TA was described in section 3.2.6. MVC was recorded during each assessment session and training torque was adjusted accordingly.

6.2.5 Ultrasound

To detect any change in muscle size, a real-time digital ultrasound imager (Technos MP, Esaote, Genoa, Italy) in B-mode was used by a single operator to collect sonographic images of the resting TA at the beginning of each experimental test

session. A 40 mm linear-array transducer (CA621, Esaote, Genoa, Italy) with a variable centre frequency (5-13 MHz) was placed over the longitudinal axis of the TA at a standardised position for all participants. The optimal position was 20% of the distance between the head of the fibula to the lateral tip of the lateral malleolus (Martinson and Stokes, 1991), an approximate location of the greatest muscle mass of the TA (Gershuni *et al.*, 1982). The transducer head was placed perpendicular to the skin along the palpable edge of the tibia and adjusted obliquely to optimise visualisation of echogenic landmarks, specifically the deep edge of the tibia, muscle fascicles and the central aponeurosis (Hodges *et al.*, 2003). Water-soluble hypoallergenic ultrasonic transmission gel (Aquasonic 100, Parker Laboratories Inc., Fairfield, New Jersey) was applied to the head of the transducer probe prior to placement onto the skin of the participant. All images were taken unilaterally on the dominant limb with the participant lying supine with their ankle held in a neutral position (McCreesh and Egan, 2011). Images were captured in triplicate and exported for later analysis offline, using publicly available software (Image J, US National Institutes of Health, available at http://rsb.info.nih.gov/ij/). Linear muscle thickness (LMTh), previously shown to reflect cross-sectional area (Martinson and Stokes, 1991), was determined as the distance between the inferior boundaries of the echogenic muscle fascia.

6.2.6 Resistance Training

The experimental groups consisted of either 12 sessions of lengthening (LEN) or shortening (SHO) resistance training only. Training consisted of 3 sessions per week. Session 1-5 and 7-11 were conducted at 80% of the relative muscle specific MVC. Sessions 6 and 12 were reduced to 50% MVC to minimise any potential fatigue during the assessment sessions. Following a warm-up set of 8 reps at 50% MVC, participants performed 5 sets of 6 repetitions at 80% MVC of contraction specific MVC at a speed of 15°/s with 2 mins rest between sets. Training was conducted under identical

conditions to the assessment sessions apart from a shorter 2 s rest period between each repetition; a detailed overview is provided in section 3.2.4.

6.2.7 Statistics

To ensure resistance training was conducted at the same relative contraction intensity between each groups, a time (Session 1 to 12) × group (SHO, LEN) repeated measure ANOVA was performed. To confirm TMS and PNS variables were assessed under the same relative torque conditions between groups and across time a repeated measured ANOVA was again performed; time, 3 (PRE, MID, POST) x group, 3 (SHO, LEN, CON).

To detect changes in MVC and in the corticospinal silent period, H-reflex and V-waves, a repeated measures ANOVA was used; time, 3 (PRE, MID, POST) x group, 3 (SHO, LEN, CON) x contraction type, 2 (Shortening, Lengthening). Finally, differences in MEPs were again assessed with a repeated measures ANOVA: time, 3 (PRE, MID, POST) x group, 3 (SHO, LEN, CON) x contraction type, 2 (Shortening, Lengthening) x contraction intensity 4 (15, 25, 50, 80% of MVC). If significance was found, an LSD *post-hoc* was used for pairwise comparisons. Additionally, 95% confidence intervals (CI) were determined to assess the magnitude of change. Statistical analyses were performed using SPSS (v17.0, Chicago, Illinois, USA).

6.3 Results

6.3.1 Training & Assessment.

There was no significant difference (P = 0.38) in relative training intensity between the SHO and LEN training groups, suggesting both groups were exposed to a similar task

specific training stimulus for their respective muscle action during the 12 resistance training sessions (Table 6.1). The repeated measured ANOVA showed no significant differences ($P > 0.05$) in relative torque across time (pre, mid, post), group (SHO, LEN, CON) and contraction type (shortening, lengthening) for any TMS variables. Similarly, there was no significant difference in PNS relative torque values ($P = 0.59$). Therefore, TMS and PNS variables were evoked under similar relative torque conditions across groups and time points.

Table 6.1. Force (% MVC) for shortening and lengthening resistance training across the 12 sessions.

	Session 1	**Session 2**	**Session 3**	**Session 4**	**Session 5**	**Session 6**	**Session 7**	**Session 8**	**Session 9**	**Session 10**	**Session 11**	**Session 12**
SHO	79.5 ± 4.0	78.6 ± 4.7	78.4 ± 6.0	79.0 ± 4.6	82.8 ± 5.7	51.7 ± 3.7	77.7 ± 7.7	81.3 ± 8.2	78.1 ± 5.7	78.7 ± 5.2	79.8 ± 3.5	50.3 ± 2.4
LEN	76.6 ± 6.2	77.7 ± 6.2	79.0 ± 4.8	78.2 ± 7.0	78.6 ± 6.2	50.7 ± 6.9	76.5 ± 7.9	76.6 ± 6.6	77.6 ± 3.3	77.6 ± 3.3	77.1 ± 4.1	49.4 ± 2.7

SHO; Shortening resistance training group, LEN; Lengthening resistance training group.

6.3.2 MVC

Figure 6.2 shows percentage change in MVC across the training period. The ANOVA revealed a significant main effect of time ($F_{(2, 56)}$ = 25.5; P < 0.001). *Post-hoc* analysis showed MVC significantly increased from pre to post training for shortening and lengthening MVC in both the SHO (Shortening MVC: P > 0.001; 95% CI 13.1 – 18.4%: Lengthening MVC: P = 0.002; 95% CI 3.70 - 14.6) and LEN (Shortening MVC: P = 0.003; 95% CI 3.30 – 14.6: Lengthening MVC: P < 0.01; 95% CI 13.7 – 24.6) training groups with no significant (P < 0.05) change in the CON group. The repeated measured ANOVA revealed a significant group-by-time interaction ($F_{(4, 56)}$ = 9.6; P < 0.001), demonstrating both experimental groups showed an increased MVC compared to the control and baseline. There was also a significant time-by-group-by-contraction type interaction ($F_{(4, 56)}$ = 6.7; P < 0.001) for MVC. The SHO group showed a significant increase in shortening MVC across time when compared to the lengthening MVC (24 vs 9%; P > 0.001; CI = 8.2 – 22.5). Similarly, the LEN group showed a significantly greater increase in lengthening when compared to shortening MVC post training (19 vs 9%; P = 0.07; CI = 3.1 – 17.4). There was no significant difference in the CON group between the action types or across time. These changes occurred with no change in muscle size (P = 0.76); Figure 6.3 shows a representative example of ultrasound images for each group across each time point.

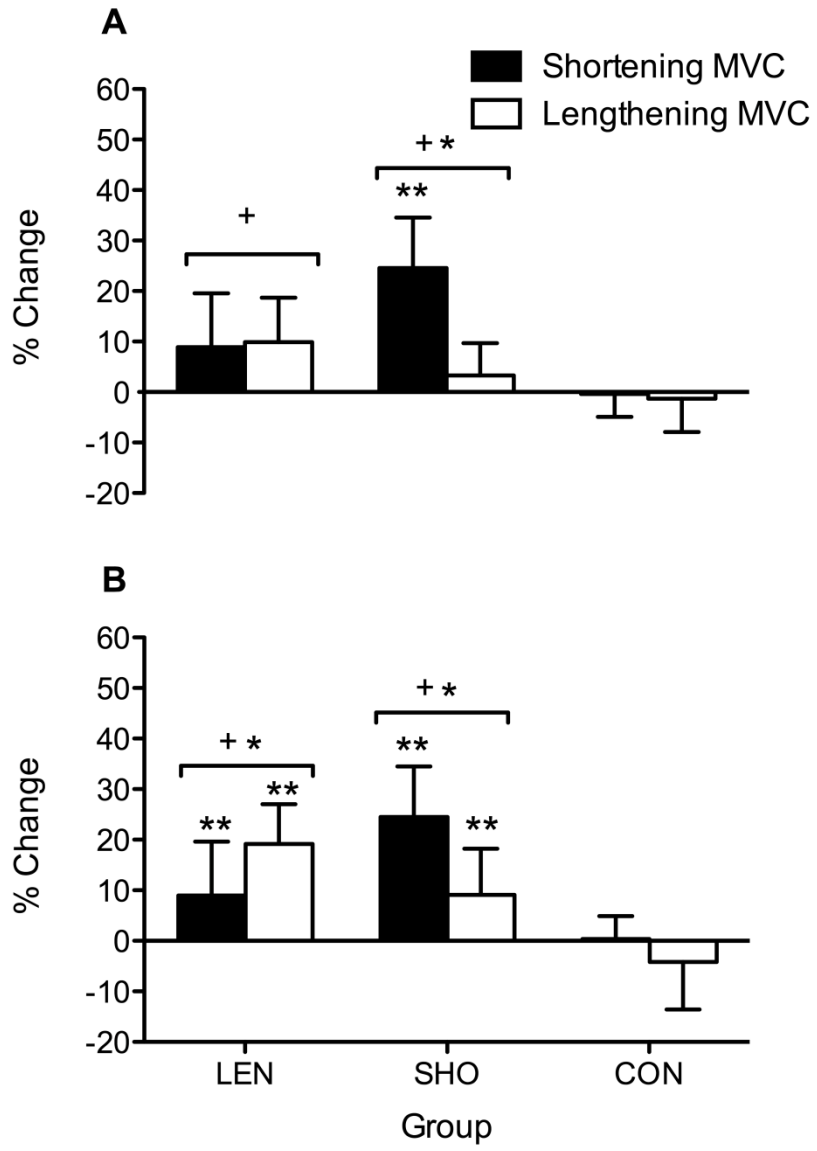

Figure 6.2. Percentage change in shortening and lengthening MVC across time (**A**) Percentage change pre to mid. (**B**) Percentage change pre to post. * denotes significant difference between muscle contractions; + significantly different to control group; ** significantly different from pre values.

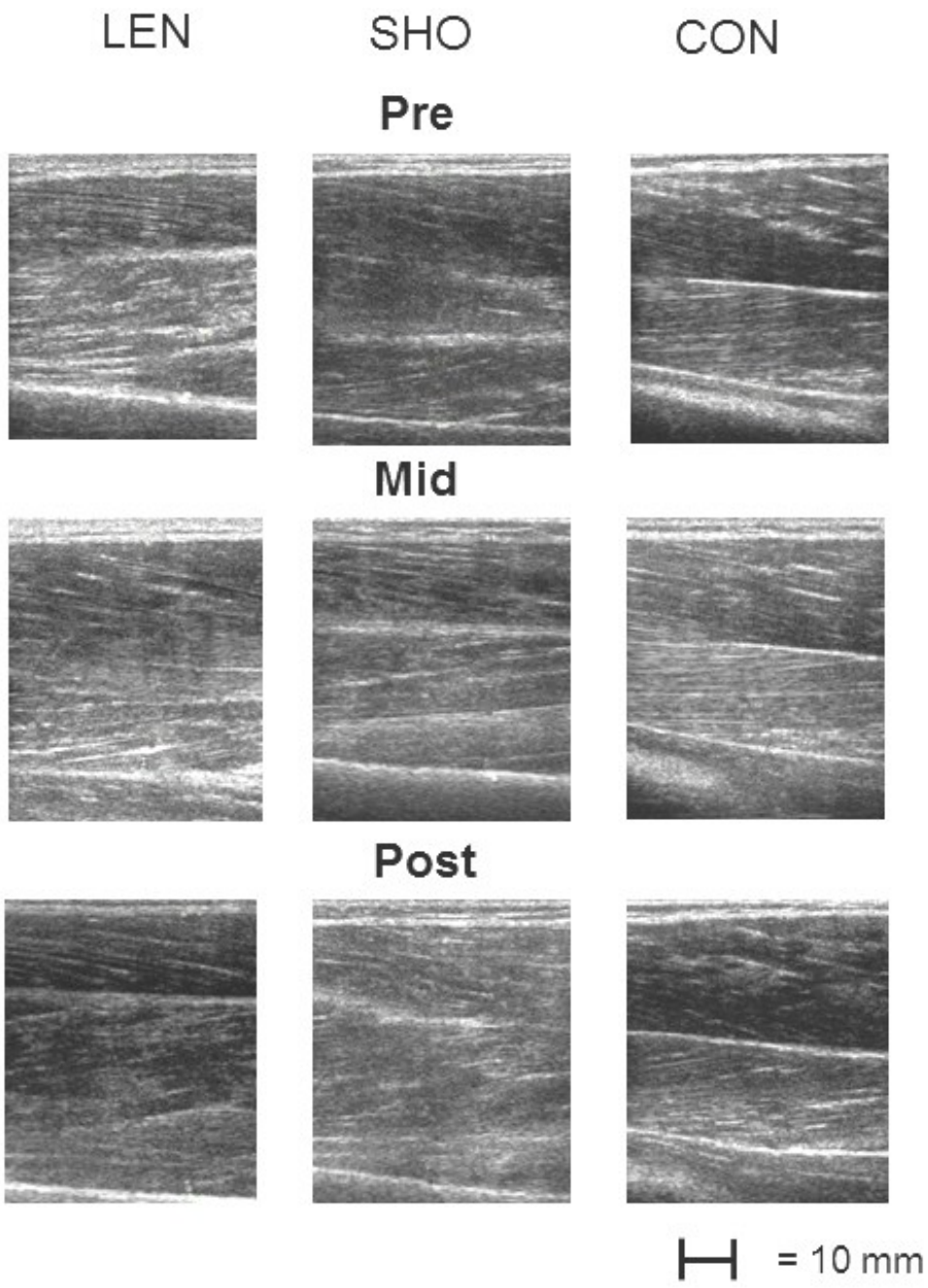

Figure 6.3 Representative TA ultrasound linear thickness images across time and groups.

6.3.3 Corticospinal

No significant (P = 0.10) change in resting MEP's was found across time (Pre – Post: LEN = 1.3%, SHO = -9.4%, CON = -8.5%); similarly there was no significant difference between groups and resting motor threshold showed no change (P = 0.17) across time

(Pre – Post: LEN = 4.4%, SHO = 3.4%, CON = 0.7%). However, there was a significant main effect of time for MEP amplitude during an active muscle contraction ($F_{(2, 27)}$ = 4.7; P = 0.01) when express relative to M_{MAX} (Fig.6.3). Pairwise comparisons revealed only the LEN group showed a significant increase in lengthening MEP amplitude from pre to post training. Differences were found at 25% (Pre- Post = 31%: P = 0.02; 95% CI 4.82 – 59.8), 50% (Pre- Post = 31%: P > 0.001; 95% CI 18.7 – 56.7) and 80% (Pre- Post = 32%: P < 0.001; 95% CI 21.2 – 57.1) lengthening contraction intensity, with changes in shortening MEP's pre to post at a contraction intensities of 25% (Pre- Post = 33%: P = 0.02; 95% CI 5.30 – 60.9). A representative trace can be seen in figure 6.5. Figure 6.6 shows MEP's expressed relative to background EMG. The ANOVA revealed a significant main effect across time when MEPs were expressed relative to background EMG ($F_{(2, 27)}$ = 18.4; P < 0.001). Significant increases were seen pre to post across all contraction intensities and all contraction types in the LEN group with no significant (P > 0.05) change at any contraction intensity in the control group. The SHO group showed an increase pre to post at intensities 50% and 80% of shortening and lengthening MVC (P > 0.05). There was also a group × time interaction ($F_{(4, 56)}$ = 4.1; P = 0.006) demonstrating both experimental groups increased compared to the control and baseline. Additionally, there was no significant change in the corticospinal silent period across time (P = 0.87).

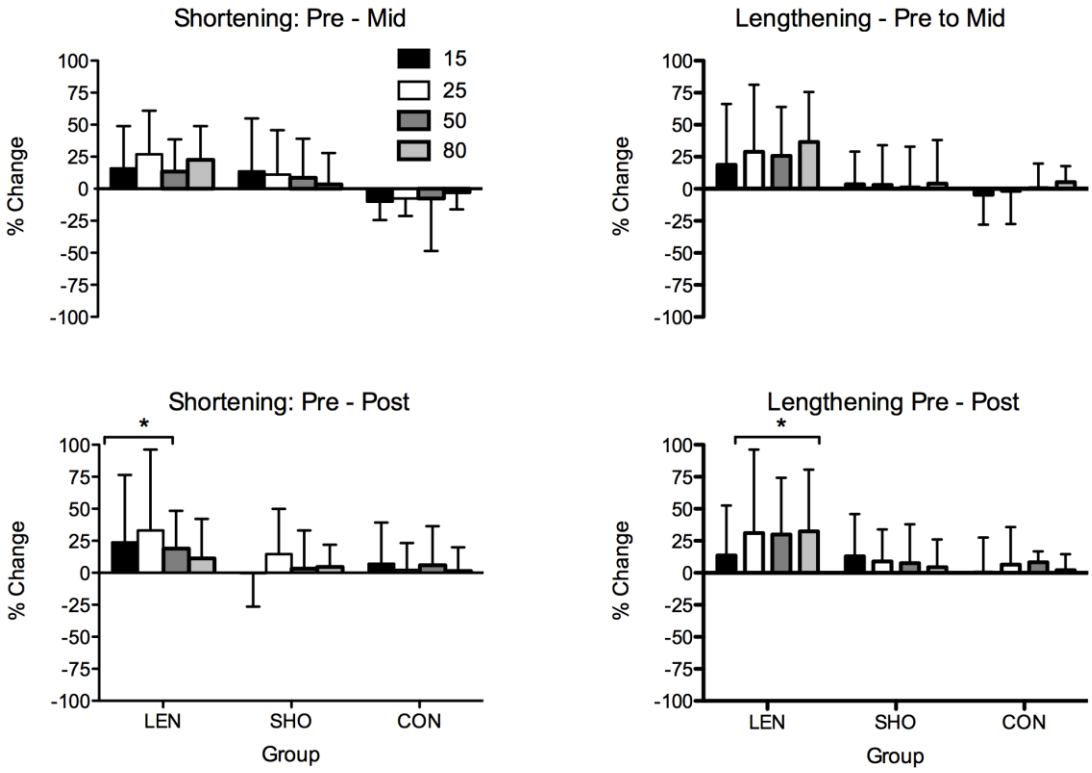

Figure 6.4 Percentage change in shortening and lengthening MEP's in each group across time when expressed relative to $M_{max.}$ * Significantly different from pre values.

6.3.4 PNS

H-reflex showed no significant difference across time or between groups when expressed relative to M_{MAX} and background EMG. Figure 6.7 shows a significant increase in V-wave amplitude across time ($F_{(2,\ 52)}$ = 6.0; P = 0.004). Pairwise comparisons revealed a significant percentage increase pre to mid (36.2% P = 0.04; CI = 2.7 – 70.0) and pre to post (66.7%; P < 0.001; CI = 44.5 – 88.9) resistance training in V-wave amplitude during lengthening muscle contractions and pre to post (25.1%; P = 0.008; CI = 7.3 – 45.3) in the shortening muscle contractions in the LEN group. However, in the SHO group, there was only a significant increase in V-wave amplitude during shortening muscle contractions pre to post only (26.3%; P > 0.009; CI = 7.3 – 45.3). No significant change across time (pre – post = P > 0.05) was found in the CON

group. Additionally, there was a significant group-by-contraction interaction ($F_{(2\ 26)}$ = 8.0; P =0.002). *Post-hoc* analysis revealed that post training, the LEN group lengthening V-wave amplitudes increased significantly more compared to the SHO (66.7 vs 9.3%; P < 0.001; CI = 29.3 – 89.4) and CON groups (66.7 vs -3.3%; P < 0.001; CI = 22.2 – 47.5).

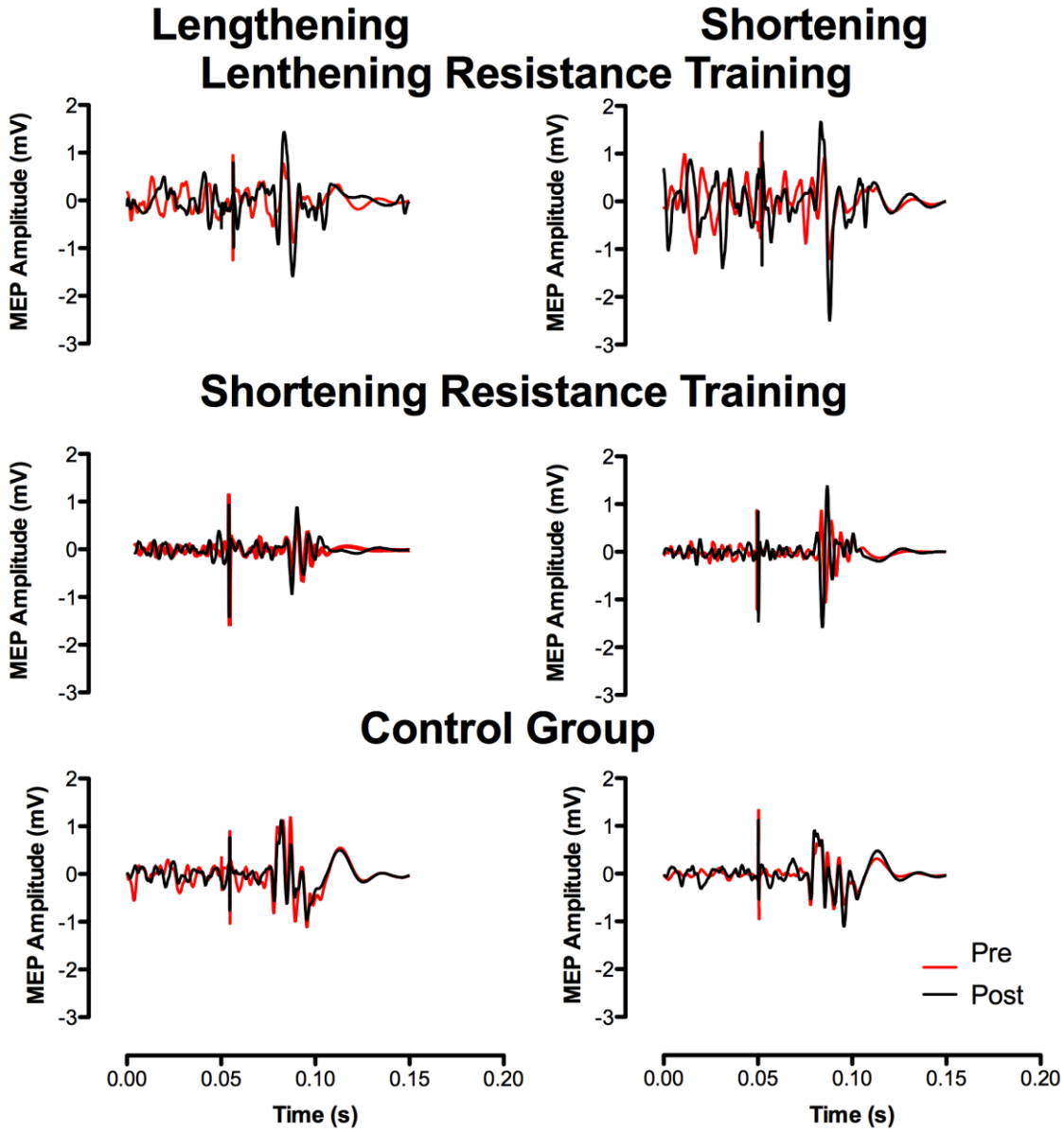

Figure 6.5 Representative traces of MEP's pre and post resistance training recorded at 80% of relative MVC.

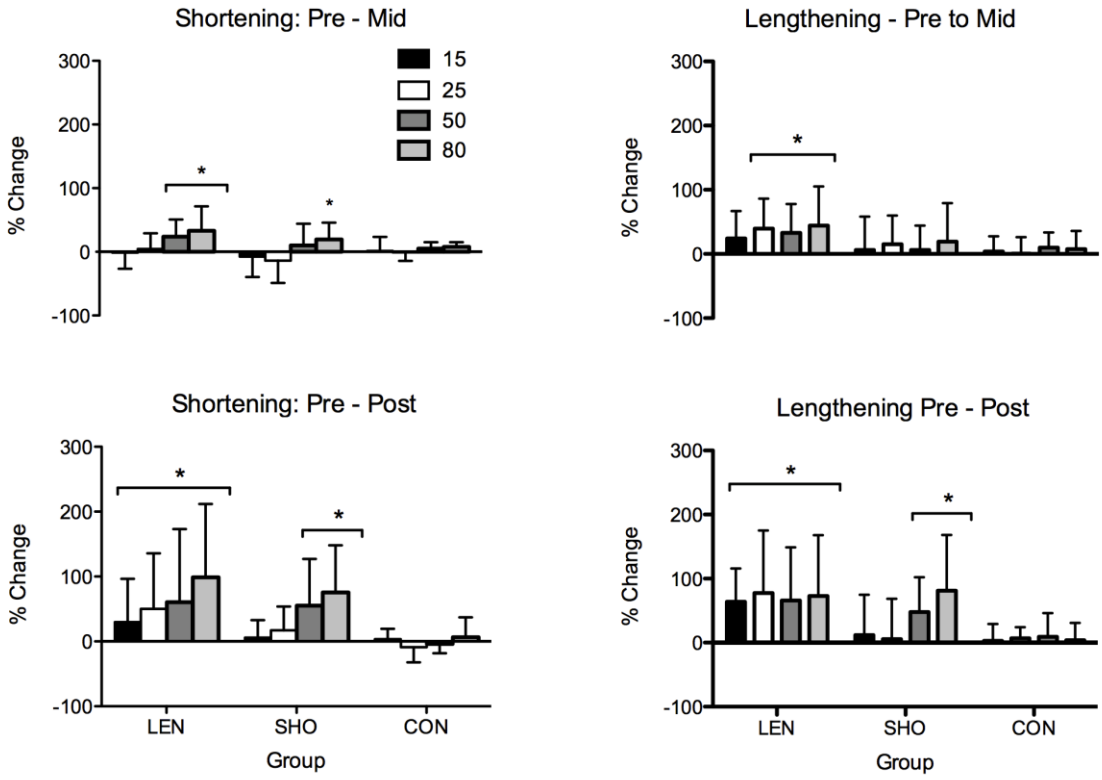

Figure 6.6 Percentage change in shortening and lengthening MEP's in each group across time when expressed relative to M_{MAX} and background EMG. * Significantly different from pre values.

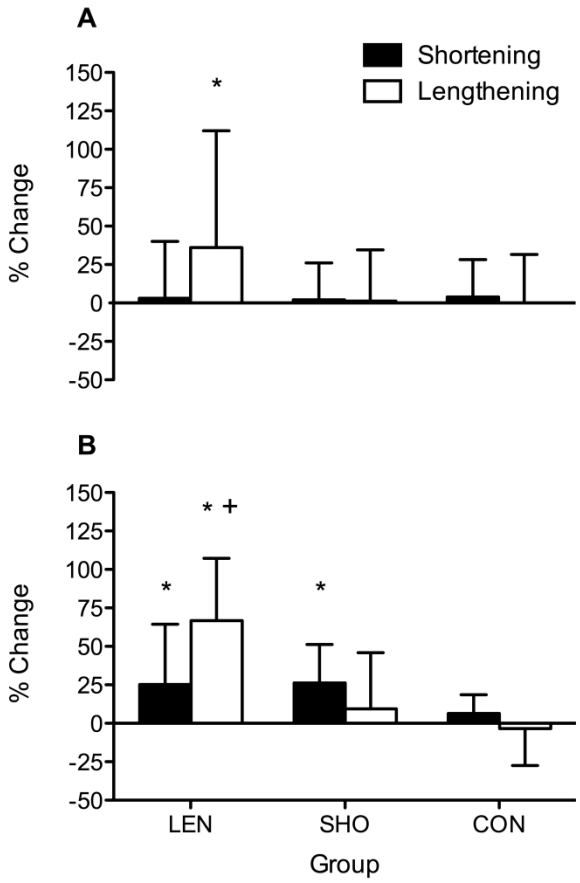

Figure 6.7 Percentage change in shortening and lengthening V-wave amplitude relative to M_{Max} across time (**A**) Percentage change pre to mid. (**B**) Percentage change pre to post. * denotes significant difference from pre values; + significantly different from SHO and CON group.

6.4 Discussion

The main findings from the first part of this chapter were: 1) Shortening resistance training improved shortening MVC more than lengthening MVC, and lengthening resistance training improved lengthening MVC more than shortening MVC in each group respectively; 2) For a set motorneuron pool (background EMG), corticospinal excitability increased for both contraction types in both groups and 3) Volitional drive increased during shortening and lengthening muscle contractions in the LEN group, but only increased during shortening muscle contractions in the SHO group. Furthermore,

lengthening resistance training increased lengthening V-wave more than shortening resistance training increased shortening V-wave.

Confirming the initial hypothesis and in line with previous research (Tomberlin *et al.*, 1991; Higbie *et al.*, 1996; Hortobágyi *et al.*, 1996; Seger *et al.*, 1998; Seger and Thorstensson, 2005; Miller *et al.*, 2006), shortening and lengthening resistance training significantly improved MVC's to a greater extent in the respective muscle contractions, thereby demonstrating task specificity. Even though conventional resistance training programmes do not overload lengthening contractions, these data further highlight the need for overloading both during shortening and lengthening contractions to maximise strength adaptations. Positive findings have been shown in the literature using this approach (Hortobagyi *et al.*, 2001).

Data has shown lengthening muscle resistance training elicits a similar strength gain to shortening when matched for the same absolute torque (Mayhew *et al.*, 1995; Raue *et al.*, 2005). Therefore it is surprising there were little differences in the magnitude of strength gains in the respective trained muscle action between the two experimental groups. Whilst the results in this chapter failed to detect any differences in the magnitude of strength gains between groups, a recent meta-analysis (Roig *et al.*, 2009) concluded that lengthening muscle contractions increase lengthening strength and total strength more than shortening. Roig *et al*. (2009) attributed the superiority of lengthening contractions to the capacity to produce higher forces and thus demonstrate a greater neurological stimulus. One possibility for the lack of detectable differences found in this chapter may be linked to the anatomical structures of the TA. The higher loads associated with lengthening resistance training cause a greater stretch on the muscle fibres compared with shortening resistance training, resulting in a greater stimulus and adaptation through the addition of extra sarcomeres (Reeves *et al.*,

2009). Previously, literature has focused on the knee extensors, however the knee extensors have notable anatomical differences to the TA. The tendon length of the TA is more than twice as long as the knee extensors (Maganaris and Paul, 2000; Andrikoula *et al.*, 2006) (TA = 160 mm vs Knee Extension = 68 mm). Based on these data, the exposure to stretch of the sarcomeres of the TA is arguably less compared to the knee extensors, due to the greater contribution of the tendon (and hence passive tension) to absorb the tension during the lengthening muscle action. Consequently, there is the potential for a reduced stimulus to the muscle during resistance training.

This study investigated neurological adaptations from shortening and lengthening resistance training at a corticospinal and spinal level. This data supports previous work demonstrating little change in corticospinal excitability at rest (Carroll *et al.*, 2002; Carroll *et al.*, 2009). The results from chapter 4 show an increase in resting MEP amplitude from a single assessment session with no change on day 3. Chapter 4 concluded that the increase in corticospinal excitability at rest could be an adaptation from the movement acquisition, possibly as a result of the familiarisation session. Supporting this, the results from this study show little change in resting MEP, further suggesting changes in corticospinal excitability at rest are not linked to increases in strength. Conversely, during an active lengthening contraction in the LEN group, there was an increase in corticospinal excitability when expressed relative to M_{MAX}. The exact reason for this observation is unclear, but may be linked to the neurological properties of lengthening muscle contractions. Hortobágyi *et al*. (1996) demonstrated a seven times greater increase in lengthening background EMG from lengthening compared to shortening resistance training. The large increases in background EMG were attributed to a greater recruitment of type II fibres (Hortobagyi *et al.*, 1996). Therefore, the increase in MEP found in this study during lengthening contractions may be due to a greater recruitment of type II muscle fibres, a heightened cortical/sub cortical

excitability and/or improved synapse and axonal efficacy as previously suggested (Carroll *et al.*, 2011).

Contrary to the results from Carroll *et al*. (2002), the results in this chapter demonstrates that when MEP's were expressed relative to background EMG, there was a significant increase in MEP peak-to-peak amplitude from pre to post resistance training. Carroll *et al*. (2002) suggested that fewer motorneurons were activated relative to background EMG due to a change in firing rates and/or intrinsic properties of motorneurons. For example, a reduced firing rate or increase in duration of hyperpolarization potential might reduce MEP amplitude during an active contraction. However, the results here provide evidence that for a set neural output there is an increased corticospinal excitability. As discussed previously, there are mixed results regarding changes in MEP's post resistance training. Different training modalities make it difficult to compare from study to study and may explain some discrepancies between findings. For example, performing precise tasks that require an element of complexity (as used for the training stimulus in this study) cannot be ruled out as a mechanisms contributing to the increase in corticospinal excitability (Taube *et al.*, 2007).

For the first time this chapter has examined changes in corticospinal excitability following lengthening and shortening resistance training. As described earlier, previous work from Hortobágyi *et al*. (1996) demonstrated a greater neurological output from lengthening resistance training during lengthening contractions, with other studies showing little differences between contraction types (Higbie *et al.*, 1996; Seger and Thorstensson, 2005; Blazevich *et al.*, 2008). This current research using TMS showed corticospinal excitability transfers across muscle contractions from shortening and

lengthening resistance training, though there is little difference in the magnitude of the change.

Maximal lengthening resistance training has been suggested to cause a decreased inhibition associated with lengthening muscle contractions (Westing *et al.*, 1990; Aagaard, 2003). Even though Chapter 5 failed to detect a reduced corticospinal inhibition in resistant trained individuals, a reduction in the inhibitory regulatory mechanism has been suggested in resistance trained individuals (Amiridis *et al.*, 1996). This chapter found no evidence of modifications in the silent period (a surrogate measure of inhibition) across the acute training period in any group, suggesting corticospinal inhibition was not responsible for increases in MEP peak-to-peak amplitude and/or strength. Previous acute resistance training studies have shown both a decrease (Kidgell and Pearce, 2010; Latella *et al.*, 2012) and no change in corticospinal inhibition (Kidgell *et al.*, 2010). Recent work using paired-pulse TMS has shown lower short-interval intracortical inhibition may occur after a period of resistance training (Weier *et al.*, 2012). However, similarly to single pulse TMS there is research showing no change following resistance training (Beck *et al.*, 2007). Therefore, exact changes in corticospinal inhibition still need to be established, though this chapter's findings suggest no differences from shortening or lengthening resistance training. Future research should include paired pulse TMS to further understand adaptions in corticospinal excitability following resistance training.

Although H-reflex amplitude is considered to be a balance between presynaptic Ia inhibition and motoneuron excitability (Aagaard *et al.*, 2002), supraspinal mechanisms have the potential to affect this measure (Gosgnach *et al.*, 2000). Consequently, despite the lack of changes in H-reflex amplitude pre to post resistance training, it is difficult to conclude with great certainty that there is no neurophysiological adaptation

at a spinal level. Previous research has demonstrated a lack of change in resting H-reflex (Aagaard *et al.*, 2002; Scaglioni *et al.*, 2002; Del Balso and Cafarelli, 2007; Holtermann *et al.*, 2007; Duclay *et al.*, 2008; Fimland *et al.*, 2009b; Ekblom, 2010), however during an active contraction, there are reports of an increased spinal excitability (Lagerquist *et al.*, 2006; Holtermann *et al.*, 2007; Duclay *et al.*, 2008). Whilst previous work has shown evidence of contraction specific changes in spinal excitability (Duclay *et al.*, 2008), the results in this chapter fail to detect any differences.

Contrary to the H-reflex, V-wave has continuously shown large changes following resistance training (Del Balso and Cafarelli, 2007; Duclay *et al.*, 2008; Fimland *et al.*, 2009c; Ekblom, 2010) of up to 80% (Gondin *et al.*, 2006a). The findings in this chapter further support this work by showing increases in V-waves in both groups; however, the data uniquely shows a greater transfer across contraction types from lengthening resistance training. Excluding the work from Duclay *et al*. (2008), who showed an increase in isometric MVC from isolated lengthening muscle contractions, little data exists on contraction specific changes in volitional drive. As described earlier, a recent meta-analysis (Roig *et al.*, 2009) found lengthening resistance training to elicit greater gains in total strength (total change in lengthening and shortening MVC). The greater transfer of volitional drive across muscle contractions from lengthening resistance training appears a possible mechanism for this adaptation. However, the findings here fail to show a greater increase in the magnitude of strength gains from lengthening resistance training.

Greater increases in volitional drive appeared to occur from lengthening training during lengthening muscle contractions when compared to shortening training during shortening contractions. Hortobágyi *et al*. (1996) attributed the large increases in EMG to a greater recruitment of Type II fibres. The H-reflex excites lower threshold motor

units, whilst the V-wave relies on high and low threshold motor units (Aagaard *et al.*, 2002). Therefore it would be logical to suggest that adaptations from resistance training in this study are due to a greater recruitment of the higher threshold motorneurons, particularly during lengthening contractions.

Whether these adaptations are due to increased excitability or reduced presynaptic inhibition is not clear with the single pulse peripheral stimulation used in this study. What seems plausible is the increase in efferent drive as a result of increased recruitment and/or firing frequency.

6.5 Conclusion

In summary, the results in this chapter show greater gains in strength from the muscle action trained. The increase in maximal muscle force generating capacity may be linked to the increase in corticospinal excitability (expressed relative to background EMG). Although corticospinal excitability did not show an indication of contraction specific adaptation, increases in V-wave appear to be greatest in the muscle contractions trained. Furthermore, the increase in V-wave amplitude was greatest from lengthening muscle resistance training, which seem attributable to the greater recruitment of type II muscle fibres.

6.6 Perspective

The final was aim of the thesis was to investigate the effect of TMS and PNS responses from acute shortening and lengthening resistance training. Whilst the results from Chapter 5 show little detectable difference between chronically resistance trained and untrained individuals, the first part of this chapter has demonstrated the

neurological system does adapt at a cortical and spinal level from shortening and lengthening resistance training. Interestingly for practitioners, adaptations appear to be greatest in the trained muscle action and thus shortening and lengthening muscle contractions should both be stimulated. Therefore, as injury risk is reduced with an increase in lengthening specific strength (Jonhagen *et al.*, 1994), it can be recommended that practitioners such as strength and conditioning coaches and physiotherapists should include lengthening resistance training at around 80% MVC. Furthermore, with the greater neurological adaptations shown during lengthening contractions, it is recommended that clinicians further consider the use of lengthening resistance training to enhance the capacity of the CNS in neurological disorders.

The first part of this chapter has added new insight into neurological adaptations to shortening and lengthening resistance training, though how the neurological system is further modulated following the cessation of resistance training is largely unknown. Therefore the second part of this chapter will address the final aim of the thesis and investigate the acute detraining response following an acute period of resistance training.

Part II: Corticospinal and Spinal Detraining Responses Following Shortening and Lengthening Resistance Training

6.7 Introduction

As the CNS rapidly adapts following the onset of resistance training and results in an increase in strength (Sale, 1988; Gabriel *et al.*, 2006; Folland and Williams, 2007), it is logical to suggest that if the stimulus is terminated, CNS adaptations and consequently strength will return towards baseline levels. Understanding how decreases in strength occur and consequently how the neurological system responds is not only important in designing tapers for elite athletes, but also furthers our understanding of detraining or inactivity in numerous other populations (Bosquet *et al.*, 2013). Although numerous studies have detected a decrease in neurological activity following cessation of resistance training (Hakkinen and Komi, 1983; Narici *et al.*, 1989), specific supraspinal and spinal alterations are unclear. It has been shown that shortening muscle contractions coupled with lengthening contractions have a greater preservation of strength, which is potentially due to the greater neurological adaptations from lengthening contractions (Colliander and Tesch, 1992). Conversely, adaptations following lengthening training have also been shown to be less susceptible to detraining (Andersen *et al.*, 2005). The second aim of this chapter was to examine corticospinal and spinal adaptations following 2 weeks of detraining.

6.8 Methods

6.8.1 Participants

Following 4 weeks resistance training, 31 of the 32 previously described participants proceeded to the second part of the study. The SHO group was reduced from 11 to 10 participants. The second part of the study comprised of 2 weeks detraining.

6.8.2 Study design

Participants completed all previously described dependent measures 2 weeks after the 4 weeks of resistance training. During the 2 weeks detraining, participants were instructed to continue to refrain for any resistance exercise.

6.8.3 Statistics

To detect changes in variables post training and following two weeks detraining, separate ANOVA's were performed. The ANOVA's were set up in an identical fashion to the training study, but with two time points (POST, DETRAIN). Significant differences were followed up with a pairwise LSD *post-hoc* test. Additionally, 95% confidence intervals (CI) were determined to assess the magnitude of change. Statistical analyses were performed using SPSS (v17.0, Chicago, Illinois, USA).

6.9 Results

6.9.1 MVC

There was no significant differences ($P > 0.05$) in relative torque (% MVC) for time (post, detraining), group (SHO, LEN, CON) and contraction type (shortening, lengthening), suggesting TMS and PNS measures were examined under the same relative intensity. Figure 6.8 shows no significant difference across time ($P = 0.09$) in shortening and lengthening MVC post two weeks detraining in any group.

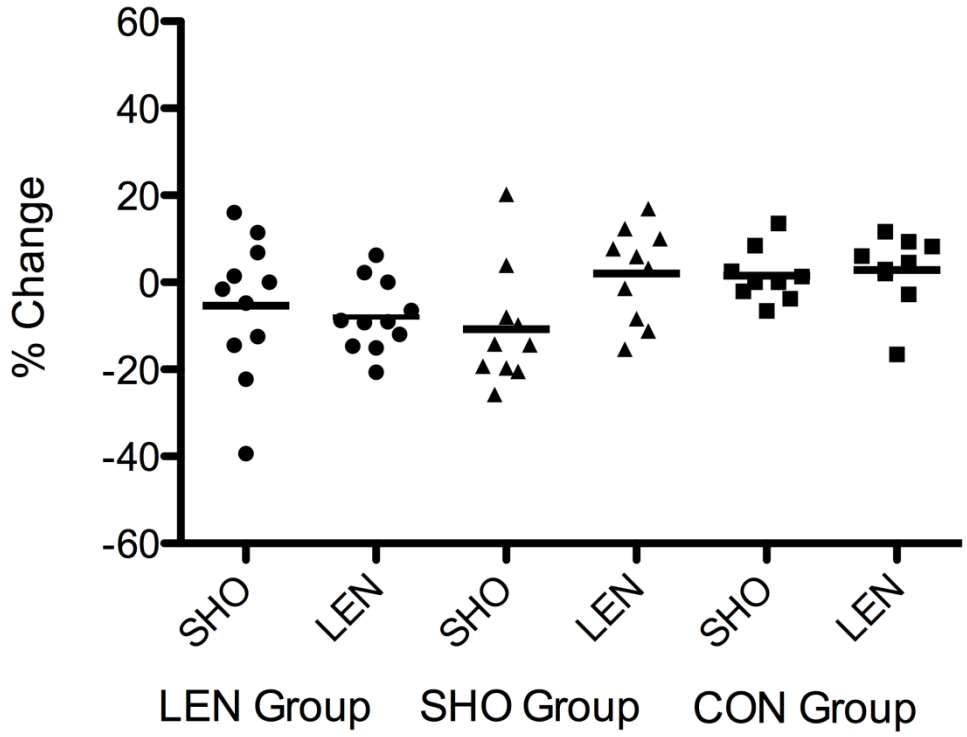

Figure 6.8 Individual and mean percentage change in shortening and lengthening MVC following two weeks detraining. Solid line represents the mean response and the symbols represent individual changes.

6.9.2 Corticospinal.

No significant difference was found post detraining for resting MEPs (P = 0.18) and rMT (P = 0.97). A representative trace can be seen in Figure 6.9. When MEP's were expressed relative to M_{MAX} there was no significant difference (P = 0.19) in peak-to-peak amplitude following two weeks of detraining. However, when EMG was taken into consideration, there was a significant decrease ($F_{(1, 27)}$ = 10.2; P < 0.001) in MEP's post two weeks resistance training (Figure 6.10). Furthermore, there was a significant group-by-time-by-intensity-by-contraction type interaction ($F_{(5, 83)}$ = 3.1; P = 0.01). Pairwise comparison revealed that the LEN group showed a significant decrease in MEP amplitude during 15% shortening MVC (-21.2%; P = 0.018; CI = 3.9 – 38.4), however. the SHO group showed a significant decrease during 50% (-39.2%; P <

0.001; CI = 19.4 – 59.1), 80% (-39.1.%; P = 0.001; CI = 18.3 – 61.8) shortening MVC and 15% lengthening MVC (-21.2%; P= 0.007; CI = 7.7 – 45.8). There was no significant change in the corticospinal silent period (P = 0.33). These changes occurred with no change in muscle size (P = 0.97); Figure 6.11 shows a representative example of ultrasound images for all groups across each time point.

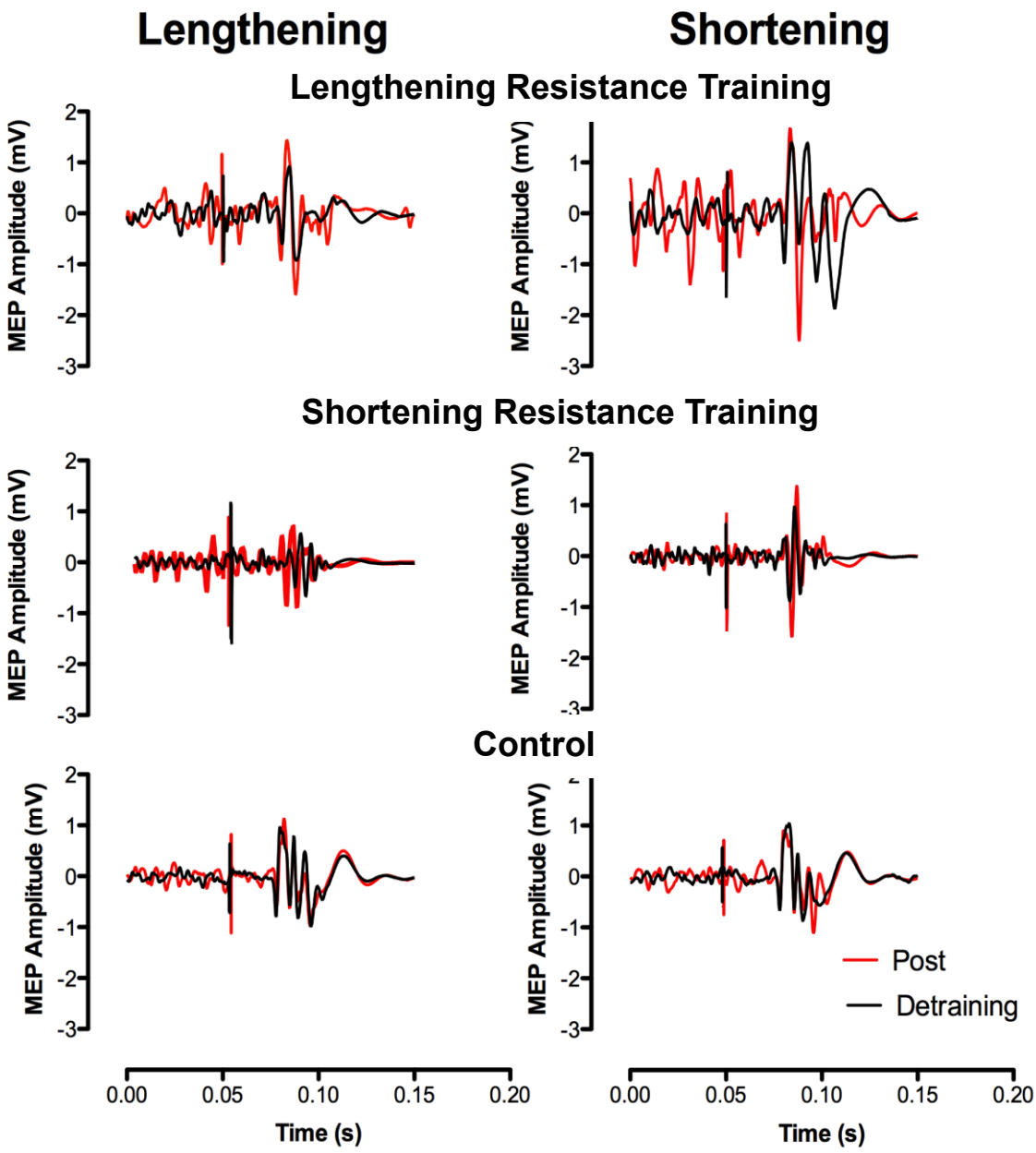

Figure 6.9 Representative traces of MEP's post resistance training and following detraining recorded at 80% of relative MVC.

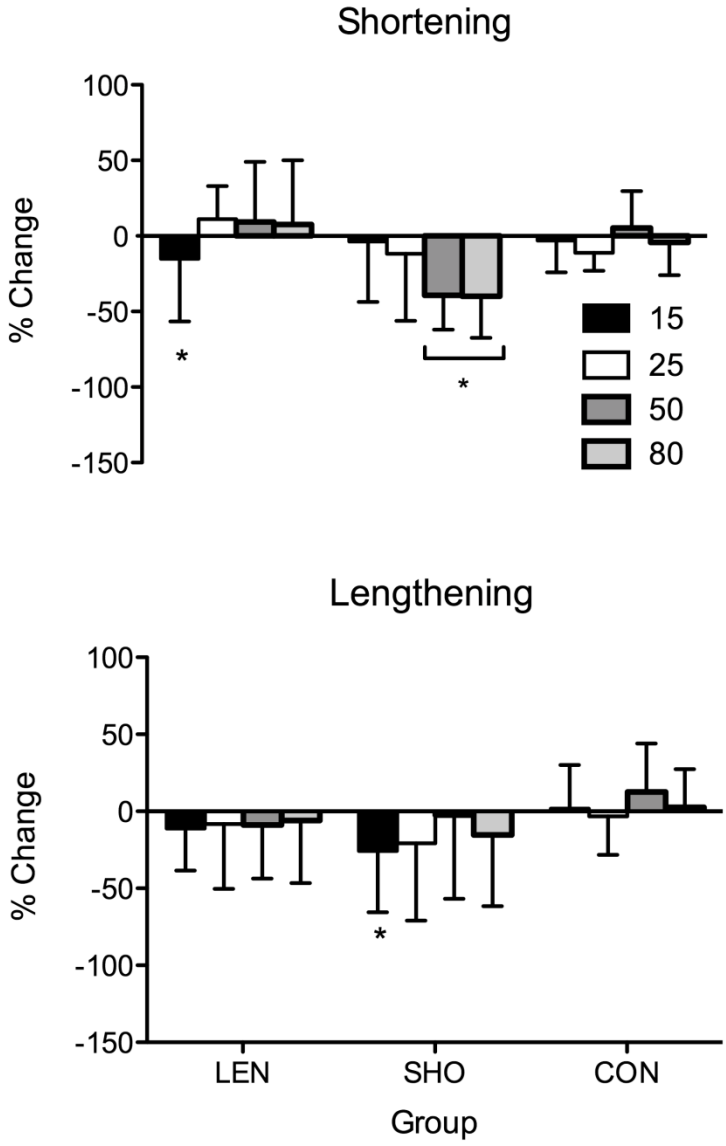

Figure 6.10 Percentage change in shortening and lengthening MEPs relative to M_{MAX} and background EMG following two weeks detraining. * Denotes significant difference from pre values.

6.9.3 PNS

H-reflex was not significantly different across time (P = 0.51), even when expressed relative to background EMG (P = 0.10). Furthermore, there was no significant different between V-waves post resistance training and following two weeks detraining for any group or muscle action (P = 0.57).

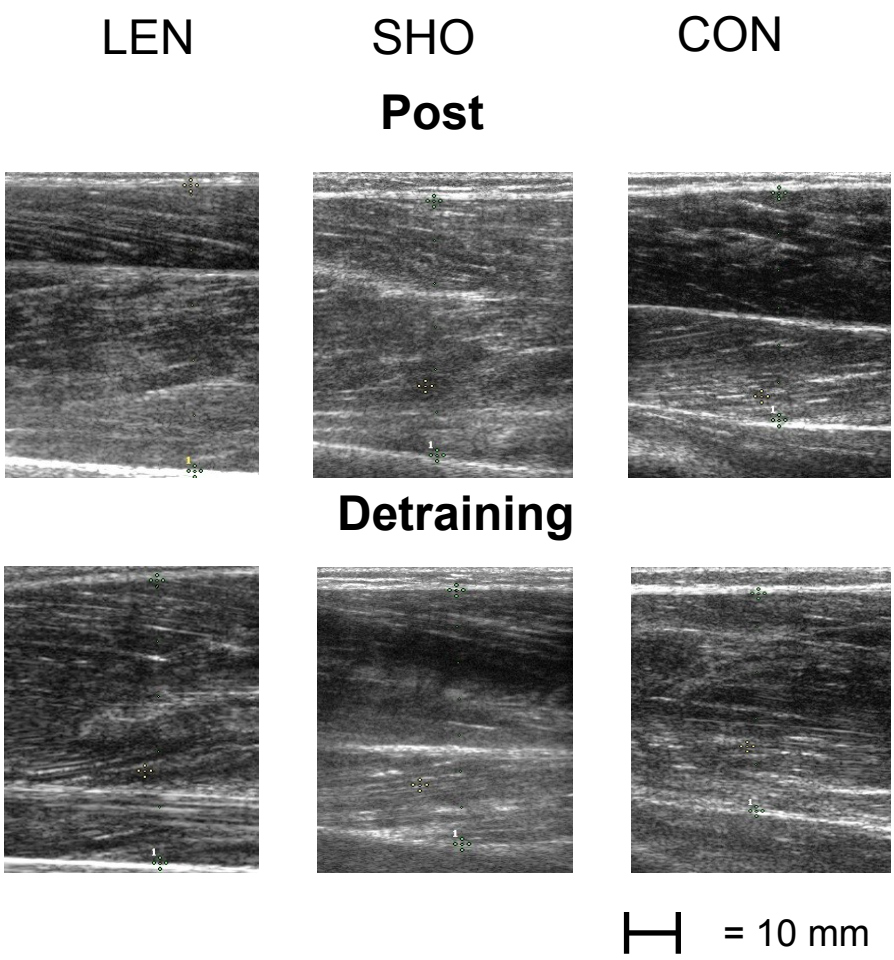

Figure 6.11 Representative TA ultrasound linear thickness images from post resistance training and following detraining.

6.10 Discussion

The second part of this study revealed: 1) Lengthening and shortening resistance training preserves maximal strength to a similar extent following a two week training period and 2) V-waves were maintained in both groups following two weeks of training cessation.

Following two weeks of detraining, there was no change in MVC in either group for either muscle action. With differences in training duration, training intensity, muscle

under investigation and muscle contractions, comparing results from different studies is not straight forward. Studies have shown an increase in strength above baseline from 4 weeks to 12 months following cessation of resistance training (Hakkinen *et al.*, 1985; Weir *et al.*, 1995; Taaffe and Marcus, 1997; Hakkinen *et al.*, 2000; Lemmer *et al.*, 2000; Brochu *et al.*, 2002; Trappe *et al.*, 2002; Harris *et al.*, 2007; Carvalho *et al.*, 2009; Popadic Gacesa *et al.*, 2011; Correa *et al.*, 2013). A recent meta-analysis concluded that following the cessation of training, a decrease in maximal force was evident in the third week of inactivity (Bosquet *et al.*, 2013). However, given the relative short duration of the resistance training programme, the variability of the detraining strength response (Figure 6.8) and the notion that longer resistance training programmes lead to longer-lasting adaptations (Bosquet *et al.*, 2013). It is perhaps a little surprising that in the current study, MVC was maintained for the period of inactivity. However, is has to be noted that all experimental groups showed a decrease in strength (apart from lengthening MVC in the SHO group) of up to 12%. Furthermore, high load lengthening exercises have been shown to cause an acute decrease in strength (Krentz and Farthing, 2010) following a short period of inactivity. These authors reported the muscle damage from the lengthening resistance training at the target muscle and surrounding joints was responsible for the suppressed MVC. Lengthening resistance training has however been suggested to be less susceptible to strength loss (Hortobagyi *et al.*, 1993; Andersen *et al.*, 2005) and coupling lengthening muscle contractions with shortening muscle contractions has demonstrated an enhanced preservation of strength (Colliander and Tesch, 1992). As lengthening and shortening MVC showed a similar decrease in strength (12 vs. 8%) from their relative training actions, the data in this chapter shows little evidence of lengthening actions preserving strength to a greater extent when compared to shortening.

Both groups showed a decrease from post resistance training MEP amplitude when expressed relative to background EMG and M_{MAX} but not solely M_{MAX}. It appears that

corticospinal excitability only decreases when adjusted for neural output. Resistance training studies have commonly shown a decrease in EMG after a period of detraining (Hakkinen and Komi, 1983; Narici *et al.*, 1989; Hakkinen *et al.*, 2000; Gondin *et al.*, 2006b). In this chapter, it is thought more neural activity (higher EMG) was needed after the detraining period to achieve the desired level of torque in the assessment session. Thus offering an explanation for the decrease in MEP when relative to background EMG in both groups. However, there was no change in strength post detraining and EMG has been shown to be preserved after months of detraining (Andersen *et al.*, 2005). Therefore, further research with a longer detraining period (>4 weeks) may provide a greater insight into the detraining responses of strength and corticospinal changes following shortening and lengthening resistance training.

There are only a limited number of studies that have investigated neurological detraining at a cortical or spinal level. Even though statistical analyses were not performed (due to n= 4), Jensen *et al*. (2005) appear to show a reduction in the MEP recruitment curve towards baseline values following cessation of resistance training. Previous research has shown conflicting results following periods of inactivity (with no prior resistance training) in rats and humans. An increase in corticospinal excitability (Roberts *et al.*, 2007), reduced cortical representation/excitability (Liepert *et al.*, 1995; Roberts *et al.*, 2010) or no change has previously been reported (Zanette *et al.*, 1997). Furthermore, reports have suggested (Clark *et al.*, 2006) that neurological factors contribute to approximately 48% of the loss in strength from inactivity. Previous work has shown neurological adaptations to last several months, and it is therefore surprising that a reduced corticospinal excitability was shown after only 2 weeks of detraining in this chapter. The reduced MEP may be a result of a cessation of the movement rather than termination of resistance training as strength did not change post detraining. Even though there was evidence of a decrease in corticospinal excitability following the cessation of resistance training, there was no evidence in this

chapter supporting the notion lengthening muscle contractions cause more long lasting neurological adaptations compared to shortening muscle contractions (Colliander and Tesch, 1992).

There was no significant change in H-reflex or V-wave following two weeks detraining. Long periods of inactivity have shown to decrease spinal excitability (Yamanaka *et al.*, 1999). As there was no change in spinal excitability during the resistance-training programme it was perhaps unsurprising there was little change following two weeks of detraining. The preservation of V-waves following two weeks of inactivity supports previous work showing that after 5 weeks of detraining there was no reduction in V-waves (Gondin *et al.*, 2006a). Even though it is difficult to compare between studies due to methodological differences, it is hypothesised that the maintenance of MVC is probably attributable to a preservation of neural drive. However, as V-wave amplitude is a result of spinal and/or supraspinal influence (Aagaard *et al.*, 2002), it is problematic determining the exact site of any potential change. As discussed previously, H-reflex amplitude did not change, although α–motorneuron excitability may still be responsible for the maintenance of MVC post resistance training as H-reflex only represents the transmission of Ia-afferents to α–motorneurons (Aagaard *et al.*, 2002; Gondin *et al.*, 2006a).

6.11 Conclusion

Even though MVC was maintained following two weeks of detraining, there was a significant reduction in corticospinal excitability (expressed relative to background EMG). As a decrease in corticospinal excitability occurred from lengthening and shortening resistance training, this chapter shows little evidence of the notion that lengthening action cause longer lasting adaptations following short duration training. V-

wave was maintained through 2 weeks detraining, suggestive that volitional drive might be a cause for the maintenance of maximal muscle strength. Longer detraining periods in combination with the use of TMS and PNS may reveal further temporal characteristics.

6.12 Perspective

The second part of this chapter addressed the final aim of the thesis and investigated the detraining response following acute shortening and lengthening resistance training. The data in this chapter suggests that from an acute period of either shortening or lengthening resistance training, strength is maintained. The first part of this chapter showed an increase in V-wave and strength following resistance training, whilst the second part showed maintenance of strength and V-wave. These data would support the suggestion that V-wave is strongly associated with changes in force generating capacity of the muscle.

Following a period of inactivity, practitioners should focus on both shortening and lengthening resistance training equally to re-train the individual. Whilst non significant, the 12% mean decrease in strength suggests that two weeks of inactivity could have detrimental effects on athletic performance. The decrease in corticospinal excitability further suggests that some CNS adaptations decrease through acute periods of inactivity. Consequently, practitioners should be aware that acute periods of inactivity have the potential to lose previously acquired physiological gains.

Chapter 7

General Discussion

7.1 Thesis Review

Maximising neurological adaptations has long been sought after to enhance athletic performance (McGuigan *et al.*, 2012) and improve the efficacy of rehabilitation programmes (Kristensen and Franklyn-Miller, 2012). As resistance training programmes consist of predominantly shortening and lengthening muscle contractions, the main aim of this thesis was to investigate the neurological adaptations to resistance training and detraining during shortening and lengthening contractions.

Chapter 4 demonstrated that TMS and PNS could be reliably repeated during dynamic muscle contraction. It was also established that an initial familiarisation session was needed 24 h before the first neurological assessment session in subsequent chapters. The second investigation compared the TMS and PNS responses in chronically resistance trained and untrained individuals. There were no detectable differences in TMS and PNS responses between the two groups, though subsequent analysis of the data found a reduction in the variability of the MEP following a familiarisation session. The final experimental chapter showed following four weeks of shortening or lengthening resistance training, there was an increase in corticospinal excitability (relative to background EMG) that was not task specific. V-wave showed evidence of contraction specific adaptations and was also greatest in the lengthening resistance training group. Following two weeks of detraining there was evidence of a decrease in corticospinal excitability (relative to background EMG) and maintenance of strength and V-wave.

7.2 Discussion

This section will initially discuss the neurological adaptations to resistance training and detraining. Following this, task specific changes in strength and neurological

adaptations from shortening and lengthening resistance training will be discussed in the second part of this section.

7.2.1 Neurological Adaptations to Resistance Training and Detraining

The series of experimental chapters have led to some interesting findings regarding the modulation of neurological factors contributing to increased force generating capacity of the muscle. Given the increasing use of TMS (Carroll *et al.*, 2002; Griffin and Cafarelli, 2007; Kidgell and Pearce, 2010) and PNS (Aagaard *et al.*, 2002; Fimland *et al.*, 2009a) to investigate neurological systems following resistance training, it was essential to establish a repeatable protocol for the first experimental chapter. Chapter 3 also adds to the existing data showing the plasticity of M1 through changes in MEP's. As previously discussed in section 7.1, there was an increase in corticospinal excitability from day 1 to 2 and then a plateau from day 2 to 3. The changes in corticospinal excitability appear to show similar temporal patterns to previous work (Muellbacher *et al.*, 2001). Muellbacher *et al*. (2001) demonstrated an increase in corticospinal excitability when participants were exposed to a new skill or motor programme. Once the pattern was learned, MEPs returned to baseline levels. This supports previous work investigating the repeatability of TMS measures (Kamen, 2004) that also showed a similar pattern with an increase in resting MEP from day 1 to 2 and a plateau from days 2 to 3. The results from Chapter 3 and the study from Kamen (2004) did not assess changes in force accuracy across the 3 days, therefore it is unknown whether the plateau in MEP was due to motor pattern being appropriately learned. However, as M1 and changes in corticospinal excitability appear to play a crucial role in the very early stages of motor learning, this assumption seems likely (Muellbacher *et al.*, 2001; Perez *et al.*, 2004; Pearce and Kidgell, 2009).

Although it was hypothesised that the results from Chapter 3 indicate changes in M1 and corticospinal excitability play an important part of motor learning, Part I of Chapter 6 suggests corticospinal excitability may increase following resistance training if the resistance training is conducted at a high intensity and is progressive. The training in this experimental chapter consisted of participants performing 5 sets of 6 reps at 80% of contraction specific MVC. Participants were assessed weekly for changes in MVC and the training stimulus was adjusted accordingly. Consequently, a continual and gradually progressive stimulus was applied to the CNS, arguably causing an increase in corticospinal excitability. Of the previous studies that have shown an increased corticospinal excitability following resistance training, all have employed contractions above 80% MVC and/or a progressive resistance training programme (Griffin and Cafarelli, 2005; Kidgell *et al.*, 2010; Weier *et al.*, 2012). However, there are numerous examples where a high intensity progressive resistance training programme has been used and shown no change in corticospinal excitability (Jensen *et al.*, 2005; Kidgell and Pearce, 2010; Latella *et al.*, 2012). Furthermore, Jensen *et al*. (2005) only showed an increase in corticospinal excitability during visual motor tasks and not during a resistance training programme consisting of up to 50 maximal contractions in each training session. Part II of chapter 6 indicated evidence of a reduction in MEP following the cessation of resistance training; nonetheless there was maintenance of strength during the two weeks detraining. Arguably, this provides further evidence that the link between corticospinal excitability and changes in strength may be negligible. The results from Chapter 5 further indicate that increases in strength do not necessarily result in an increased corticospinal excitability. A unique finding from Chapter 5 part II is the suggestion that resistance trained individuals show a greater neurological plasticity to a new stimulus compared to untrained individuals. From a familiarisation session, a reduction in MEP variability was seen from day 1 to 2, though why this only occurred during resting MEPs is unclear.

Using single pulse TMS, previous work has shown a reduction in corticospinal inhibition following resistance training (Kidgell and Pearce, 2010; Latella *et al.*, 2012). The findings in this thesis suggest that corticospinal inhibition is not altered following resistance training, whether this is from acute resistance training as shown in Chapter 6, or in chronically resistance trained individuals as shown in Chapter 5. Recent work using a paired pulse TMS paradigm that explores specific inhibitory circuits in M1 showed a reduction in intracortical inhibition (Weier *et al.*, 2012), though there has also been non significant findings (Beck *et al.*, 2007). Consequently, future research should focus on using pair pulsed TMS to explore specific circuits that might contribute to the adaptive response following resistance training.

Chapter 6 extends the existing literature that demonstrate notable adaptations in spinal reflexes from resistance training (Aagaard *et al.*, 2002; Fimland *et al.*, 2009a; Ekblom, 2010) and showed no change in H-reflex following acute resistance training. Previous work has shown an increase (Aagaard *et al.*, 2002; Lagerquist *et al.*, 2006; Holtermann *et al.*, 2007; Duclay *et al.*, 2008) and no change in H-reflex amplitude (Beck *et al.*, 2007; Del Balso and Cafarelli, 2007; Fimland *et al.*, 2009a; Ekblom, 2010; Vila-Cha *et al.*, 2012). Despite H-reflex being assessed during an active muscle contraction, the data in chapter 6 suggests that there is little modification in the Ia afferent loop from acute resistance training. The results from Chapter 5 further support this, showing no detectable differences in H-reflex in untrained compared to chronically resistance trained individuals; however, it could be argued that the training status of the TA in resistance trained individuals is a relatively untrained muscle. This suggestion is further reinforced with no differences reported in V-wave in the same chapter. In muscles that are exposed to a chronic training stimulus, an increase in V-wave amplitude has been shown compared to non-athletes (Casabona *et al.*, 1990; Nielsen *et al.*, 1993). Therefore, it would appear that the TA has no detectable neurological adaptations following chronic exposure to a dynamic resistance training programme. Nevertheless,

Chapter 6 has provided clear evidence that V-wave is increased when the TA is directly exposed to dynamic resistance training through dorsiflexion and planter flexion of the ankle. This supports the growing body of research (Sale *et al.*, 1983a; Aagaard *et al.*, 2002; Gondin *et al.*, 2006a; Del Balso and Cafarelli, 2007; Duclay *et al.*, 2008; Fimland *et al.*, 2009a; Fimland *et al.*, 2009c; Ekblom, 2010; Vila-Cha *et al.*, 2012) demonstrating that a heightened volitional drive may be one of the primary mechanisms for increasing the force generating capacity of the muscle.

7.2.2 Adaptations to Lengthening and Shortening Resistance Training and Detraining

In agreement with previous research, Chapter 6 has shown evidence of task specific adaptations from resistance training with no evidence of a greater increase in lengthening MVC from lengthening resistance training compared to shortening MVC from shortening resistance training, which is supported by numerous other studies (Higbie *et al.*, 1996; Seger and Thorstensson, 2005; Miller *et al.*, 2006). The task specific adaptations in strength demonstrated in Chapter 6 further emphasise the importance of performing both high intensity shortening and lengthening muscle contractions as part of a balanced resistance training programme, although in reality, the lengthening phase is under loaded because it is capable of generating more force than shortening muscle contractions. As a consequence, a conventional resistance training programme has been shown to elicite a smaller gain in lengthening MVC compared to a solely lengthening overloaded resistance training programme (Hortobagyi *et al.*, 2001; Reeves *et al.*, 2009), further highlighting the use of isolating lengthening muscle contractions in resistance training programmes.

Many acute muscle injuries occur from an overload in force during the lengthening phase of a contraction (Pulla and Ranson, 2007). For example, hamstring lengthening MVC is less in sprinters with a history of hamstring injuries (Jonhagen *et al.*, 1994). Additionally, performing lengthening contractions has been shown to reduce the risk of falls in the elderly through a greater ability to resist load in anti gravity movements (LaStayo *et al.*, 2003) and to be an effective tool to increase strength in cardiovascular diseased patients (Meyer *et al.*, 2003). Based on these data, a greater emphasis should be directed towards ensuring lengthening contractions are conducted at higher contraction intensities, to maximise strength and neurological adaptations. This in turn may assist and reduce the injuries in athletic populations and improve the quality of life in clinical populations such as the elderly.

Previous work has shown a greater maintenance of lengthening strength (Andersen *et al.*, 2005) following resistance training. The second part of Chapter 6 revealed that shortening and lengthening strength is maintained to a similar extent, two weeks following the cessation of resistance training. This was despite a non-significant decrease in 12% shortening MVC from shortening resistance training and an 8% decrease in lengthening MVC from lengthening resistance training. A recent meta-analysis has shown that strength loss is evident after 3 weeks following the cessation of resistance training (Bosquet *et al.*, 2013) and consequently a longer period of detraining may have detected differences between the two training groups. The second part of chapter 6 also showed a very variable decrease in strength between participants, which may have contributed to the non-significant findings. Nonetheless, following two weeks of inactivity, it can be concluded that strength is on average preserved, which is potentially valuable information to help tapering strategies for athletes and understand the consequence of periods of inactivity in other populations.

Chapter 5 revealed no detectable neurological differences between chronic resistance trained and untrained individuals during shortening and lengthening contractions. During lengthening muscle contractions, resistance trained individuals have shown a lack of a superimposed torque compared to untrained individuals (Amiridis *et al.*, 1996). The authors suggest that lengthening muscle contractions have a tension regulating measure that is down regulated from resistance training. The lack of differences found in Chapter 5 may be due to the methodology used to assess neurological adaptations in this thesis. For example, the TMS and PNS techniques used in this thesis did not directly assess the tension regulating mechanisms during lengthening contractions such as co-activation of the antagonist muscle and golgi tendon organ activity. Future research should also consider using twitch interpolation to further investigate adaptations following shortening and lengthening resistance training.

As discussed in section 2.4, lengthening contractions are suggested to have a greater supraspinal output (Fang *et al.*, 2001; Fang *et al.*, 2004) and greater inhibition at a spinal level (Duclay and Martin, 2005; Duclay *et al.*, 2008) compared to shortening contractions. Despite the differences previously reported, there were little differences in task specific changes following resistance training in corticospinal excitability (when expressed relative to background EMG). It would appear that changes in excitability at corticospinal level are similar between muscle contractions and not task specific.

A reduction in the tension regulating mechanism during lengthening contractions may be a primary cause for the greater increase in V-wave from lengthening resistance training. As lengthening contractions produce a greater force, and thus are conducted under greater tension, a down regulation in the sensitivity of the golgi tendon organ may be a unique adaptation specific to lengthening contractions. Further research using paired pulse PNS (Knikou, 2008) would be needed to investigate this suggestion.

The lack of changes in H-reflex in all experimental chapters indicates that inhibition of the Ia pathways may not be a primary adaptation from resistance training, though H-reflex was only recorded during 25% MVC and may not be representative to a resistance training intensity of 80% MVC. Furthermore, the lack of changes in corticospinal inhibition in Chapter 5 and 6 suggests the role corticospinal inhibition has in the force generating capacity of the muscle is minimal. Whilst this series of studies offers an insight into the neurological mechanism responsible for increased strength from shortening and lengthening resistance training, the exact mechanisms still need to be explored.

In conclusion, it would appear that lengthening training causes a greater increase in V-wave from acute resistance training. The suggestion is that differences in neurological adaptations between lengthening and shortening may reside at a spinal level. This thesis provides evidence that the Ia afferent loop is not a contributing factor in this experiment, but cannot be ruled out completely. Furthermore, the influence corticospinal excitability has on force generating capacity of shortening and lengthening appears negligible.

7.3 Limitations and Future Recommendations

Through innovative techniques this series of investigations has enhanced our understanding and added greater clarity to neurological adaptations from shortening and lengthening resistance training and subsequent detraining, however it has also raised further questions. Further understanding of the strength and neurological adaptations following shortening and lengthening training and detraining can optimise resistance-training programmes and potentially inform clinical practice and those involved in human performance.

Despite Chapter 5 adding to the small body of research investigating the neurological adaptations in chronically resistance trained individuals, it could be argued that the muscle examined in this thesis (the TA) is not a muscle that is specifically targeted in a conventional resistance training programme. Therefore, future research could benefit from exploring how the neurological system is modified in chronically resistance trained individuals in a muscle such as the quadriceps that is frequently targeted in resistance exercise regimens. Including other techniques such as twitch responses along side MEP, silent period, H-reflex and V-waves, will also help improve our understanding of longer term adaptations. Performing these neurological assessments during conventional resistance training exercises, such as knee extension, may provide a more appropriate assessment, though accessibility of the femoral nerve for techniques such as H-reflex may be difficult. Future research should also use more advanced paired pulse techniques to further understand the modulations of the neurological system following resistance training. Recent resistance training literature has used pair pulsed TMS to investigate intracortical inhibition (Latella *et al.*, 2012). Furthermore, the use of cervicomedullary stimulation and TMS has led to some interesting findings regarding the difference in the neurological control strategies between isometric and lengthening contractions (Gruber *et al.*, 2009). More specifically, Gruber *et al*. (2009) showed differences in the MEP/CMEP ratio between lengthening and isometric contractions. Understanding how the ratio is modified between these two variables may generate information to locate where the adaptations occur along the corticospinal tract following resistance training.

At a spinal level, the conditioning stimulus has been used to investigate presynaptic inhibition of Ia afferent, reciprocal inhibition, Ib inhibition and recruitment inhibition (Knikou, 2008), although how these cortical and spinal mechanism are modulated from lengthening and shortening resistance training is unknown. Using more advanced

spinal techniques, particularly during dynamic muscle contractions, would further our knowledge regarding acute and chronic adaptations to resistance training.

The detraining period in the second part of Chapter 6 was two weeks. A recent meta-analysis has shown strength loss evident in the third week following the cessation of resistance training (Bosquet *et al.*, 2013). In addition, assessing individuals during a longer detraining period and at more regular time points throughout a longer detraining period will increase our knowledge regarding the temporal characteristics of detraining and inactivity. Consequently, practitioners will be able to make more informed decisions regarding tapers with athletes and will understand the period of inactivity in the elderly better. For example, if we can understand the appropriate rest following a high intensity, resistance training programme to maximise strength and minimise the detraining response, then practitioners can increase the efficiency of resistance training programmes. Future research should also focus on patient populations. Maximising strength and neurological adaptations to resistance training is crucial for improving the quality of life in patient populations such as stroke and the elderly. This thesis has provided data showing the need for overloading both shortening and lengthening contractions to maximise contraction specific adaptations. How the neurological system is modified from shortening and lengthening contractions in these patient populations is largely unknown.

The series of investigations have presented new data that can be used by clinical practitioners, applied sport scientists and researchers to enhance their working practises. From a research perspective, it is now understood that TMS and PNS related measures can be reliability repeated in the TA during dynamic contractions. This method can be used to assess changes in neurological conditions such as foot drop. This thesis has further enhanced the need for performing overloaded lengthening

contractions to maximise lengthening MVC, which may help improve the quality of life in the elderly (LaStayo *et al.*, 2003) and reducing the risk of injury in athletes (Jonhagen *et al.*, 1994). The data in this thesis has shown a greater increase in volitional drive from lengthening resistance training, clinical practitioners that want to maximise neurological adaptations should include lengthening contractions. Whilst strength did not decrease significantly during the research in this thesis, there was a strength loss of up to 12% after 2 weeks, with a high variability of the response between individuals. Strength and conditioning coaches should therefore understand their individual athletes' detraining response. Furthermore, following a period of inactivity, practitioners should focus on both shortening and lengthening contractions equally.

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Appendix A

Participant no	Ethics Code	Chapter 4	Chapter 5	Chapter 6 Part I	Chapter 6 Part II
1	REL3 & LEN006	X	X	X	X
2	REL5	X	X		
3	REL6 & SHO15	X	X	X	X
4	REL7 & SHO07	X		X	
5	REL8 & CON09	X	X	X	X
6	REL9 & CON03	X	X	X	X
7	REL10	X	X		
8	REL11	X	X		
9	REL12 & LEN20	X	X	X	X
10	REL13 & LEN26	X	X	X	X
11	REL14	X	X		
12	REL15	X	X		
13	REL16	X	X		
14	REL17	X	X		
15	REL18	X	X		
16	REL19	X	X		
17	REL20 & SHO08	X	X	X	X
18	REL21 & LEN001	X	X	X	X
19	REL22	X	X		
20	REL23 & CON5	X	X	X	X
21	SHO2			X	X
22	CON4			X	X
23	LEN10			X	X
24	CON11			X	X
25	SHO12			X	X
26	SHO13			X	X
27	CON14			X	X
28	LEN16			X	X
29	CON17			X	X

30	CON18	X	X
31	LEN19	X	X
32	CON21	X	X
33	CON22	X	X
34	CON23	X	X
35	LEN24	X	X
36	LEN25	X	X
37	CON27	X	X
39	LEN28	X	X
40	LEN29	X	X
41	CON30	X	X
42	CON31	X	X

Appendix B

Eligibility Checklist

ID _____ Date_____

How old are you? (18 to 40) _____ Weight _____ Height _____

If you answer yes to any of the following questions you are not eligible to take part in the study.

Have you ever broken a bone in your leg or foot?

Do you have pain in your legs or foot?

Have you ever been diagnosed with a neurological disorder?

Have you ever been diagnosed with a brain disorder such as Parkinson's disease?

Have you ever had a stroke?

Do you have any metal objects in your head?

Are you taking any medications that you know would affect neuronal conduction?

Do you have a pacemaker?

Have you had any operations involving your heart?

Do you have a metal plate in the skull, metal objects in the eye or skull (for example after brain surgery or shrapnel wounds)?

Are you pregnant or seeking to become pregnant in the near future?

The information I have given is correct to the best of my knowledge at the time of completion.

Signature of Participant.....Date.....

Appendix C

INFORMED CONSENT FORM

Project Title: The reliability of methods used in the quantifications of neurological adaptations to strength training

Principal Investigator: Jamie Tallent

Participant Number: _____

	please tick where applicable
I have read and understood the Participant Information Sheet.	☐
I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.	☐
I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.	☐
I agree to take part in this study.	☐
I would like to receive feedback on the overall results of the study at the email address given below. I understand that I will not receive individual feedback on my own performance. Email address……	☐

Signature of participant..... Date.....……..

(NAME IN BLOCK LETTERS).....…….

Signature of Parent / Guardian in the case of a minor

.....

Signature of researcher..... Date.....……..

(NAME IN BLOCK LETTERS).....…….

Appendix D

Prior to data collection, the raw analogue signal (mV) from the isokinetic dynamometer was converted to force (N·m). Regression analysis (Figure 1) was performed across the expect range of forces expected throughout the thesis. Data was collected using Signal 3.0 (Cambridge Electronics, Cambridge, UK).

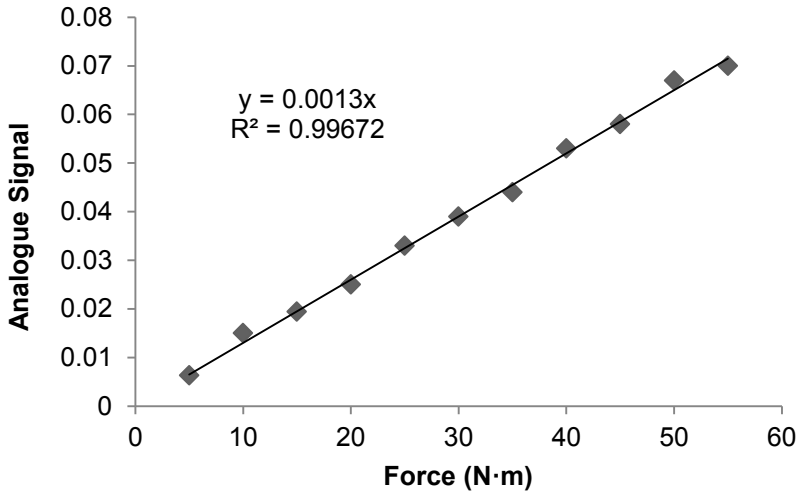

Figure 1: Regression analysis for the raw analogue signal.